Metallurgical characterisation of 1st and 2nd century AD Roman copper-alloy military equipment from north-western Europe

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Abstract

Roman military equipment has traditionally been studied from a typological perspective based on a linear concept of change. Whilst Roman alloys have been analysed scientifically and general studies on them have been published, analysis of military equipment has been scarce and mostly secluded as part of excavation reports of individual sites. Scientific analysis though, can provide independent ways of studying military equipment. It can answer questions about production and distribution of the raw materials and finished objects and is capable of informing on reasons for technological choices (the intention of obtaining determinate colours, for example), and identification of military units.

A total of 216 copper-alloy military objects from the British sites of South Cadbury Castle, Ham Hill, Usk, Carlisle, Chester and Kingsholm, and the German site of Kalkriese were selected for obtaining metallurgical characterisation: chemical analysis at major, minor and trace element level and microstructural analysis to obtain fabrication history and identifying any plating. The analytical techniques employed were atomic absorption spectrometry (AAS), scanning electron microscopy with energy dispersive x-ray spectrometry (SEM-EDS), optical microscopy and multivariate statistics methods such as principal component analysis (PCA), discriminant analysis (DA) and multivariate analysis of variance (MANOVA). The aim of the project was to characterise the chemical and physical make-up of Roman military copper-alloy metalwork from the 1st century AD, with especial interest in the immediate post-conquest period.

The results of the analysis show a difference between the Roman military equipment from British sites and the equipment from Kalkriese, based on trace element patterns. This difference can be explained by a large input of material into Britain that had been made in the years before AD43 in preparation for the conquest. Contrary to recent scholarship, and based on compositional and microstructural evidence, some *lorica segmentata* brass fittings seem to have been centrally produced. Primary brass and specific gunmetal compositions seem to be associated with the military and probably chosen primarily for their appearance and resemblance to gold, rather than for their mechanical properties. The possibility of mechanised production of brass is explored based on the brass ingot from Sheepen.

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Chapter 1: Introduction

1.1 Background

Typological studies of body armour, swords, helmets and numerous types of fittings have traditionally been central to the study of Roman military equipment. The variation seen in the archaeological record is now explained as a complex series of interactions working simultaneously driven by cultural and technological change, in opposition to the traditional view of linear change over time (James 2002; 2012; Bishop & Coulston 2006).

The best approach for studying the material is probably to start with completely independent ways. Whilst the study of metals defined by major elements can be used to identify intentional alloying, quantification of trace elements is needed for an adequate chemical characterisation. Extensive studies of Roman alloys, such as those by Craddock (1978) and Dungworth (1995) have focused on 'alloy type' studies of general Roman use of copper alloys that sometimes has included military equipment. However, another independent method of analysis, metallography, can provide essential information for the fabrication processes of the objects and whilst it has been used in the past for iron weaponry and armour (Lang & Williams 1975: Tylecote & Gilmour 1986; Fulford *et al* 2005), it has been little explored in the case of copper-alloy military objects.

Metallurgical analysis of Roman military equipment has normally involved only those elements defining alloy type in Roman copper alloys: zinc, tin and lead, and the techniques of analysis employed in these cases (such as x-ray fluorescence) are not suitable for quantifying elements present at trace levels.

Some trace elements such as nickel, silver and cobalt are associated with the copper used for alloys such as brass and are more likely to survive close to their original levels through metallurgical processes such as smelting and re-melting. Attempts to trace copper-alloy objects back to the original ore have not been successful due to the effects of smelting and extensive recycling (Craddock 1976; Hauptmann 2007; Pernicka 1999). However, it could still be possible to associate trace element patterns to a workshop or tradition even with a recycling system present.

Reece (2002) cast his doubts about Roman military units being a material reality seeing them as more a textual concept and mentioned that no material studies have been able to identify the existence of units with any success. However, Ponting (2002; 2006) showed that it was possible to

show differences between military metalwork from Gamla and Masada by analysing trace elements. Whilst major alloy constituents were similar for both sites, differences were noted in the case of certain trace elements: nickel and arsenic contents were higher in the objects from Masada and silver values were higher for the material from Gamla (Ponting 2002: 566).

Microstructural analysis has often been neglected in archaeometallurgical studies of copper-alloy object because of its destructive nature, but is frequently the only way to obtain information about the fabrication history of an object or to assess mechanical properties such as strength or hardness. Additionally, it is sometimes crucial to detect and investigate the remains of plating applied to an object and even to obtain information about post-application heat treatment to enhance the durability of the plating.

This thesis represents the first stage in large-scale study of characterisation of Roman military equipment employing both chemical analysis and microstructural techniques.

1.2 Research Statement

216 samples taken from Roman military objects mostly from the first and early second centuries AD were analysed to obtain a metallurgical characterisation. The objects were found on the sites of Cadbury Castle, Ham Hill, Usk, Carlisle, Chester, Kingsholm and Kalkriese (see Chapter 4) and are variously held in the Museum of Somerset (Taunton), the National Museum of Wales (Caerleon), the Tullie House Museum and Art Gallery (Carlisle), the Gloucester City Museum and Art Gallery and the Varusschlacht Museum & Park (Kalkriese, Germany). The sites are mainly associated with legions *II Augusta*, *XX Valeria Victrix* and the legions *XVII, XVIII* and *XIX*. The analysis techniques employed were atomic absorption spectrometry (AAS), scanning electron microscopy (SEM) with energy-dispersive x-ray spectroscopy (EDS), which were integrated with metallographic analysis and multivariate statistics analysis including principal component analysis (PCA) and discriminant analysis (DA) (see Chapter 3). The research addresses issues of the identification of units through metallurgical characterisation (major, minor and trace elements), and production scale, location and the possibility of mechanised production (employing microstructural analysis).

1.3 Objectives

The main objective of this thesis is the metallographic and chemical characterisation of Roman copper-alloy military equipment and the use of these data to identify different units and/or workshops through metallurgical analysis.

1.4 Aims

The general aims of this thesis are to improve the knowledge of the production processes and modes of production of Roman military equipment during the first century AD. This includes discussing the places of production and the possibility of mechanized production. Another aim of the project is to investigate the importance of colour, identity and display shown through the equipment of the Roman army.

1.5 Overview of Chapters 2-7

Chapter 2 offers an overview of the accumulated and current knowledge on Roman military equipment including diverse aspects of the topic. A summary of the history of the subject is given, followed by existing documentary and representational evidence including sculpture, tombstone and terracotta statuettes. The ways that military equipment can be attested archaeologically are then summarised and biases in the archaeological record are acknowledged. The following sections present typological and 'change' studies that have attempted to explain the archaeological record and reconstruction studies that have aimed to understand how the equipment performed in battle. Published theories of modes and scale of production are then summarised, followed by sections on ownership, identification and personalisation of equipment. A summary of general scientific analyses on Roman metallurgy and Roman military equipment are preceded by a description of Roman ferrous and non-ferrous (specifically copper and some of its alloys: bronze and brass) alloy production.

Chapter 3 presents the methodology of analysis and descriptions of the analytical and multivariate statistics techniques employed in this thesis. First, a definition of the copper alloys used by the Romans is given. This is followed by an enumeration and definition of the major, minor and trace elements measured in this thesis, according to their presence in Roman copper alloys. The advantages and limitations of archaeometallurgical techniques are then discussed and the choice of the techniques used in this thesis is explained. This is followed by a description of the process of selection of the assemblages (and possible biases are acknowledged and discussed), including the type of equipment sampled and the assemblages temporal framework. After the sampling methods and sample size are discussed, the analytical techniques used in this thesis, their operational principles, sample preparation and analysis procedures are described, and specific methodological

considerations (including limits of detection and performance on standard reference materials) are addressed: atomic absorption spectrometry (AAS), scanning electron microscopy with energy dispersive spectrometry (SEM-EDS) and optical metallographic analysis. This is followed by a brief explanation of the multivariate statistics techniques employed on the trace element data.

Chapter 4 offers an overview of the assemblages analysed and a brief description of the sites associated with them. The sites are South Cadbury Castle, Ham Hill, Usk, Chester, Kingsholm and Kalkriese. Each section corresponds to an assemblage and includes a table with sample name, description of each object, a photograph and information on context and publication when available. Since the assemblages analysed are mainly associated with legions *II Augusta, XX Valeria Victrix* and *XVII to XIX* in Kalkriese, a summary of the positioning of the legions can be found at the end of the chapter.

In Chapter 5 the results of the analyses are presented first on a site by site basis and then considering all the sites together. In each case the alloy-type composition of the assemblage is followed by a discussion of the trace elements and then by the SEM and optical metallographic analysis of sections taken from the objects. The final section of the chapter presents the results of multivariate statistics analysis employing the trace elements measured, which show a statistically significant difference between the assemblages from the British legions (*II* and *XX*) and the German units at Kalkriese.

Chapter 6 integrates the results from the previous chapter by discussing alloy-type technology and selection and their association with the military, the difference with pre-Roman Iron Age assemblages, the high-importance of colour and display shown by the Roman army, the suggestion of centralised production for certain *lorica segmentata* fittings, the possibility of mechanized production and the identification of units by studying the trace element concentrations and offering an explanation for the difference observed between legions *II* and *XX*.

Chapter 7 presents the conclusions of the thesis and suggests steps to continue the project of characterization of Roman military equipment.

Chapter 2: The Research Context

2.1 Introduction.

In this chapter a panorama of Roman military equipment research up to the early 21st century is presented, including the relevant documentary, representational, reconstruction and archaeological studies. The integration of these sources has proven useful in tracking changes in military equipment across the history of the Empire, as well as to reveal complex issues of ownership and disposal, 'specificity', expressions of identity, and production. In recent years these problems have also been informed by scientifically-based analysis on the equipment of different alloy types. This chapter seeks to show that metallurgical studies are an independent way of addressing questions pertaining to Roman military equipment studies, a field which, for the most part, has relied on typological analysis.

2.2 Roman military equipment studies

The equipment of the Roman army has long drawn the attention of scholars, as there has been an implicit recognition of the army as a centre of power, a vehicle of change and as a robust framework that supported an empire to last for 500 years.

For centuries, perceptions of the Roman army were shaped by literary and representational evidence, with the latter being almost totally responsible for how people conceptualised military equipment. Nevertheless, in the past the actual objects themselves were appreciated according to beliefs held at specific periods of time. In the Middle Ages for example, Roman spearheads were valued primarily as relics from the time of Christ, while the people of the Renaissance admired them specifically as weapons of the past (Fischer 2012) giving way to the mixture of collecting and nascent scholarship of the antiquarians of the 16th and 17th centuries.

It was not until the nineteenth century that archaeological work began to be structured more formally as typologies began to be established from the finds. Construction of typological series was a typical approach of the time, one which tended to emphasise style over metallurgical form or content. In 1892 the Reichslimeskommission was created and finds from the excavations at the forts of Niederbieber (1820-9), Zugmantel (from 1760 onwards), Saalburg (1853-62), and Eining (starting in 1879) were published in the reports sponsored by the Kommission. This period was followed by the excavation and publication of Enns (Lauriacum) and Vienna (Carnuntum) in 1900 by

Maximilian Groller von Mildensee, material from Numantia by Adolf Schulten (1905-1912), Hofheim by Emil Ritterling in 1912, and excavations of sites in Britain, such as Richborough and Hod Hill, and forts along Hadrian's Wall, such as Newstead (Curle 1911). The Limeskongress at Durham University in 1949, brought together the most important branches of Roman military studies, in particular British and German scholars, and would eventually include military equipment finds. In later decades Graham Webster (1969) and Jürgen Oldenstein (1976) provided works of synthesis concerning military equipment in general, and from the mid-Empire *Germania* and *Raetian limes*, respectively (Fischer 2012). Experimental archaeology flourished at the same time, with Peter Connolly (1975) and Henry Russell Robinson (1975), who published a volume specifically dedicated to imperial armour, developing helmet typologies and making the first functional reconstructions of Roman segmental armour, *lorica segmentata*; Marcus Junkelmann's experiments in which men in full (reconstructed) 1st century legionary kit marched from Verona to Augsburg (500kms) generating a month of experiential knowledge (Junkelmann 1986); the creation of re-enactment societies, especially the Ermine Street Guard, who have been organizing displays using reconstructed equipment and contributing with practical knowledge of the life of soldiers within the Roman army since 1973 (Haines *et al* 2000). Important catalogues of military equipment studies in these years include those of Augst, Windisch, and Xanten (Unz & Deschler-Erb 1997; Precht 1993).

Roman military equipment had been studied through typological and stylistic analysis that suggested a 'logical' evolution and presenting quite clearly differentiated stages. A simple mono-linear explanation in the tradition of Webster (1969), Connolly (1975) and Russell Robinson (1975) for change and/or production has recently given way to more balanced approaches that take in to account more mechanisms for variations and life-cycles of different types of equipment (Bishop & Coulston 2006; James 2012).

Traditionally, images of legionary and auxiliary equipment during the first centuries of the principate show a legionary soldier equipped with a short sword (*gladius*), a dagger, a short javelin (*pilum*), a rectangular shield (the Gallic flat form, or the Samnite concave), a 'Gallic' type helmet (*galea, cassis)* and a cuirass (*lorica*) (Le Bohec 1989; 1994); whereas infantry auxiliaries are traditionally pictured with a longer sword (*spatha*) and a spear (lancea, *hasta*), and as comparatively less well protected than their cavalry counterparts. However, the degree to which legionary and auxiliary equipment could be discernible from each other is not clearly understood (Maxfield 1986).

An enormous variety of Roman military equipment from legionary and auxiliary context was brought to attention through conferences in the 1980s. The publication of the proceedings of the regular cycle of Roman Military Equipment Conferences (ROMEC), from 1982 onwards and those of

Roman Frontiers Studies and the Roman Archaeology Conference have brought major contributions to the field but also are very significant in reflecting the dominance of British and German scholarship in the field. Most important in bringing together material from diverse parts of the Roman world are the volumes of the *Journal of Roman Military Equipment Studies* (*JRMES*), a multilingual journal that began in 1990 and deals with material from the Republic to the Byzantine period. That said historically there has been a strong geographical bias towards equipment in the Western part of the empire, especially the north-west, but important projects on other frontiers exist , such as those on Morocco (Boube-Piccot 1980), Dura Europos (James 2004), Zeugma (Gschwind 2009), Herodium and Masada (Stiebel 2003; Stiebel & Magness 2007), and Dülük Baba Tepesi (Fischer 2011).

Knowledge about military equipment and its role in the army acquired thus far has been synthesised in three of the most important books on military equipment, Bishop and Coulston's *Roman Military Equipment* (1993; 2006), James' *Rome & the Sword* (2012) and Fischer's *Die Armee der Caesaren* (2012).

Roman military studies have benefited from a change of focus during the last decades following a general tendency in archaeology, from an "army-as-institution to soldiers-as-people approach" (James 2002: 42). Science-based analysis is fit to contribute as an independent aid to this multi-dimensional strategy (Tite 1991; Jones 2004). From the middle of the 20th century, science-based analytical techniques became widely applied to archaeological research, resulting in the long term in positive synergies that began to permeate all branches of archaeology (Jackson 1990; Craddock 1978; Craddock & Lambert 1985; Ponting & Segal 1998; Ponting 2002).

2.3 Documentary and representational evidence

The first way to study Roman military equipment was through a documentary approach. History was a literary genre in antiquity. There should, however, be caution when trying to interpret what ancient historians tell us about the past, as they tended to alter facts according to their own political views or literary purposes (Roth 2009: 3-4). Ancient Roman writers on military matters include a mix of playwrights, poets and historians including Plautus, Virgil, Lucan, Silius Italicus, Juvenal, Velleius Paterculus, Tacitus, Frontinus Arrian, Dio Cassius, (the Pseudo-) Hyginius, and Vegetius. However, very little is said about such mundane matters as military equipment. While there are technical works such as those describing artillery works (Vitruvius), military equipment is usually just mentioned in a casual way. For example: Tacitus (*Hist*oriae 2.42) mentioned helmets,

breastplates, swords, and shields used to push in close quarters; Arrian (writing during the time of Hadrian) wrote about oblong shields (*Techne Taktike,* 4.4); Ammianus Marcellinus (writing in the 4th century AD) mentioned textile caps worn under helmets (*Res Gestae* 19.8.8), helmet plumes (*Res Gestae* 16.12.24) , infantry wearing mail armour, and heavy armoured cavalry (*Res Gestae* 45.10.8); or Vegetius (late-4th/early-5thcentury), who described the transverse crests of centurial helmets, or mentioned the intimidating effect of shining armour on the enemy (*Epitoma rei militaris* 2.14.8).

Representational evidence poses similar problems, as its objectives did not necessarily include realistic depictions of soldiers and their equipment, as much as it involved art and propaganda. This kind of source cannot be interpreted independently from the archaeological evidence and indeed other representational or documentary sources. Paintings, monuments, tombstone reliefs, and terracotta figurines are typical examples of representational evidence.

Depictions of Roman military equipment in art have been considered in some detail (Waurick 1983). However, weapons and armour in Roman art differ frequently from the contemporary reality, as revealed through archaeological finds. For instance, it seems that for mythological or historicizing themes, historical Greek armour, such as the Attic helmet, was sometimes employed in representation, despite the obvious anachronism (Waurick 1989).

Monuments, such as Trajan's Column, acted in a similar way by showing a visual representation of the equipment. The Column was erected to celebrate the victory of Rome over the Dacians (AD101-2 and 105-6), a fact which should suggest caution in interpreting the figures on its reliefs. There is a degree of uncertainty in the realism in Trajan's Column (Bishop & Coulston 2006: 5). As a source of information about how the soldiers were equipped on the relief it has to be taken with care, always keeping in mind the original context of such a monument. The message that the Column was intended to deliver was propagandistic and/or symbolic in nature. For instance, in one of the panels on the Column (LeBohec 1994, Plate 14.8-16) some soldiers wear armour even when working as builders of a fortification. However, there is still a degree of veracity in the equipment seen on Trajan's Column, as attested by archaeological finds of *lorica segmentata* (plate armour) and rectangular convex shields, for example. The Column shows other problematic features. Inconsistency in conventions, figures in wrong positions, and artistic conventions resulting in disproportion in the apparent size of depicted equipment, are all present. The audience to whom the monument was directed is of essential importance in understanding the Column, which displays an emphasis on citizenship and employs pictorial language that would have been understood in the urban environment of Rome. Praetorians could have been employed as models for both citizen and auxiliary types on the Column and construction techniques in the capital likewise might have

influenced the fortifications appearing on it. The Column's style would also influence later 2nd and 3rd centuries sculptural depictions in Rome (Bishop & Coulston 2006: 5).

When comparing the figures with the contemporary ones on the metopes from the Troapeum Traiani at Adamklissi, Romania (Furtwängler 1903), legionary infantry appears differently equipped, while the auxiliary troops are identically represented on both monuments (Coulston 1989). Apparently Trajan's Column depicts legionaries (citizen troops) with the rectangular *scutum* wearing *lorica segmentata,* while auxiliaries are shown using *lorica hamata* (mail armour) and oval-shaped shields decorated with wreaths, eagles, rosettes, stars, and crescents (Fischer 2012). In contrast, on the Adamklissi monument, legionaries are all represented wearing *lorica hamata* and *squamata* (Fischer 2012). Bishop (2011) points out that in actuality there must have been differences between troop types so that Trajan's Column could serve its propagandistic purpose and highlight legionary citizenship. At Adamklissi, local variations in weapons and equipment are probably closer to the actual military equipment used at the time (Goldsworthy 2003: 17).

An example of artistic license in representational media is given by Coulston (1988a) when examining a sandstone relief at Croy Hill (Strathclyde). Three figures are depicted holding shields with a trapezoidal profile. Coulston argues that the shape was chosen to suggest perspective, and did not represent the actual shape of the shield.

Tombstones and terracotta statuettes are more likely to represent the factual appearance of the equipment, as they were produced in an environment closer to the material that is depicted on them, or at least they emphasise certain items that were carriers of hierarchy or identity meanings. In particular military equipment may have a connection with the position of the soldier within the military and society in general (Bishop & Coulston 2006). This is explained by their fabrication from the point of view of the soldiers themselves or their relatives. On first to second century AD tombstones at least one of these elements can be seen: *cingula* with 'apron', infantry *paenula* or cavalry *sagum*, a *gladius* or cavalry *spatha*, a *scutum* (rectangular, hexagonal or oval and carried on the right hip), *hastae* for auxiliaries, *pila* for legionaries; a helmet, and *lorica hamata* or *lorica squamata*. At the end of the second century the equipment seems to have changed according to tombstones in the Danube area, with the *sagum*, long-sleeved tunics, worn by all soldiers, and *hastae* increasingly replacing *pila*. The *cingulum* now shows a ring-buckle almost always, and its presence denotes a soldier being depicted. The sword is now carried on the left hip, and chapes are usually flat and round, or pelta-shaped. Body armour does not feature frequently on the tombstones of the late second century AD (Coulston 1987).

Terracotta statuettes, as a three-dimensional medium, have been an aid to a better morphological and typological understanding of military equipment. These were mainly produced in the north-western provinces, such as Gaul (van Boekel 1989). A wide range of horse harness types and their parts, such as saddles, girths, and straps, are known and have been described with a certain degree of detail. Van Boekel writes that Bishop (1988: 88-9) reports similarities in harnesses on funerary monuments with military connotations, although they are not simplified as in the terracotta figurines (the figurines do not show girths, for example). However it is not known whether these terracotta figurines have military connections.

As noted above, chronology and change are sometimes reflected in representational evidence. For example, on the Column of Marcus Aurelius, Weisenau type helmets (Imperial Gallic) that appeared on Trajan's Column are now replaced by other helmets that do not match the archaeological record (neither the Niederbieber type, nor its predecessor, the Weisenau type's successor) and are interpreted as stylized variants of helmets actually used. Plate armour is present in lower numbers than on Trajan's Column and squared shields are completely absent, suggesting that fashion in representation and actual change in equipment are in some measure represented on the Column (Waurick 1989). However, the three types of armour known in the archaeological record are represented on the Column of Marcus Aurelius: Roman soldiers are depicted in some battle scenes wearing *lorica segmentata* or *hamata* (Ferris 2009: pl. 59, 82) whilst in other scenes *lorica squamata* can also be seen represented along with the other two armour types mentioned (Ferris 2009: pl. 64, 74, 77).

Chronological representations however, are then again subject to contemporary artistic conventions. It has been thought that the infantry of the 3rd and 4th centuries abandoned the use of armour since monuments and tombstones from the period show only cavalrymen wearing it (Coulston 1986). However armour is seen again on representational sources by the time of Theodosius I (late 4th century [Coulston 1990: 143]). The absence of armour in representations was most likely due to artistic convention rather than an actual abandonment of its use, as can be attested by 3rd century finds, where iron mail and copper-alloy scales have been found on sites in Upper Germany and Raetia, and at Carpow (Scotland), Caerleon (Wales), Vimose (Denmark) and Dura-Europos (Syria). The same situation had already presented itself in funerary reliefs from the 1st century. Artistic representations could have combined different conventions with contemporary details (Coulston op. cit.).

2.4 Archaeological studies

2.4.1. Mechanisms into the archaeological record

According to Bishop (1991) the presence of military equipment on sites in the first century at least, usually denotes the presence of the army, a situation that accounts for the majority of military finds. The Webster hypothesis associates the presence of objects of military equipment to a site occupied by the army, by attributing a high probability of military presence to a site where two or more military objects are found.

Military equipment can be attested archaeologically by deposits found in forts that had been buried prior to abandonment, burial rites, dedications, battlefield finds, or accidental loss. It could also enter the archaeological record as booty or through trade (Bishop 1989; 2011). The ways in which military equipment could have entered the archaeological record might be summarised as follows:

- Military equipment in burial contexts only became more relevant during the late empire as Germanic and trans-Danubian cultural practices influenced the army so that weapons and armour were buried with their owner (Bishop & Coulston 2006). Some burials reflecting exceptional circumstances offer military equipment that was actually used, such as the burial in Velsen, (Netherlands; Morel & Bosman 1989), where a man was killed, probably during a rebellion (in AD28?), and deposited in a well together with a dagger, several copper belt plates and a buckle, covered with a silver foil. However, burials are generally funerary depositions that may not be a reliable source for assessing what soldiers wore in reality. Spearheads can be found in graves, even in cremations, together with ritually broken weapons (Fischer 2012). They may not however be military kit, but as much the hunting equipment of rich individuals (Willems 1989). Some of the buried equipment may relate only to an individual, such as a nobleman, since it was not normal for legionaries or auxiliary soldiers to be buried with their equipment, but civilians sometimes were (Bishop 1989). Such a situation could be exemplified by the iron weapons found in a cremation burial context in a Roman villa near Vorendaal in the Netherlands (Willems op. cit.). Military equipment in burials could also be a sign of social position. For example, from the third century on, the only military objects deposited in burials are belts, which seemed to be regarded as appropriate items to represent a soldier's status (Petculescu 1995).
- Dedications of equipment in watery contexts seem to be biased towards weapons and helmets, possibly prized items, over armour or other fittings, such as belt plates (Bishop

2011). This bias could also be caused by fittings being preferably recycled instead of being deposited, or that the chances of recovery are smaller. Dedications of equipment include the Danish bog finds from Ejsbol, Illerup Adal, Nydam, Thorsberg, and Vimose (Jensen *et al* 2003; Ilkjaer 2003; Grane 2007). However, these bog finds could also be explained as being the result of illegal trade (Rald 1994) or booty. Modern interpretation of the objects can also obscure dedication. For example, according to Clarke and Jones (1994) some of the pits found at Newstead contained material that could have been associated with human agricultural fertility, and not necessarily being just rubbish.

- Finding equipment on battle sites, e.g. Kalkriese (Rost & Wilbers-Rost 2010), Harzhorn (Geschwinde *et al* 2008), Döttenbichl (Zanier 1994), or Dura-Europos (James 2004) is not frequent. Roman soldiers did not engage in battles often, and dead soldiers were normally stripped of all equipment after the battle. Additionally, some of the captured items could have been burnt or deposited in rituals. Post-combat and pre-deposition processes on battle sites are very complex and are associated with very specific circumstances, for example at Kalkriese, where part of the looted equipment had been gathered together and not recovered later (Rost & Wilbers-Rost 2010); at Dura-Europos, where a Roman countermine collapsed killing 20 soldiers and thus preserving their equipment (James 2004); or probably finds in rivers, such as at the Rhine near Mainz, or in the Po near Cremona (Fischer 2012).
- Hoards represent objects that were buried to hide them from enemies, imminent danger, or collected following plundering after conflict, with the intention for them to be recovered at a later time, as with the Corbridge and Newstead assemblages, or the cave finds in Hebron linked to Hadrian's campaign of AD132-135 against the Jews (Fischer 2012: 88-92). Hoards of cavalry equipment, such as those found at Doorwerth, Fremington Hagg, and Seven Sisters (Jenkins *et al* 1985; Allen 1905), or the group of objects found at Xanten-Wardt (which is probably loot from *Vetera* I; Schalles 1994), together with some of the objects found outside the Empire, which could have been booty from cross-border incursions.
- Chance and probability do not seem to have played a significant role in the loss of military equipment. According to Bishop (2011), accidental losses are inversely proportional to size and functionality: small decorative fittings would be more likely to be lost than weapons or helmets. However, the presence of small fittings could also be due to caching for re-cycling.
- Abandonment is probably the most important mechanism for sourcing of military artefacts, and a very significant amount comes from military installations and their vicinities. The location of finds of equipment in forts or fortresses, in ditches or pits, has been important when interpreting the meaning of its distribution. The location of the pits is related both to

the way the fort was demolished and to the location of troops within the fort (Bishop 1986). Frequently, equipment found in fort ditches is interpreted as intentional deposition, as the army would have buried scrap equipment not considered worthy of carrying away before abandoning a fort, such as in Corbridge or Newstead (Bishop 2011).

On other occasions equipment found in a fort might be marking the location of *armamentaria* or workshops. **I**n general, areas where the military situation was complex and sites were frequently abandoned will tend to produce more finds of military equipment than those with a stable situation and long period of occupation, since most of the finds can be attributed to intentional deposition in advance of fort abandonment (Bishop 1985a). These objects could be part of a scrap stock including repaired items, as was found in Carlisle (Bishop & Howard- Davis 2009).

The area between the Rhine and the Elbe rivers has yielded a surprisingly large amount of small metal finds, considering that there are no traces of violence in the military camps. This is probably due to the fact that the time camps were occupied was short, and they had been vacated leaving objects that otherwise would have been reused. Still, destroyed camps usually yield a larger number of objects: for example Cáceres el Viejo, in Extremadura, destroyed in 80BC during the Sertorian War; the Augustan camp of Haltern, destroyed in AD9 leaving a large number of metal finds; those camps destroyed during the Boudiccan rebellion of AD60/61 or the civil wars of 68-70, such as Vetera I, Hofheim, Rheingönheim, Aislingen or Burghöfe (Ritterling 1913; Ulbert 1959; 1969; Müller 2010), were all left with a significant amount of military equipment.

2.4.2 Biases in the archaeological record

Objects made of metal, bone or ivory are more likely to stand the passage of time, and of this material, projectiles such as arrowheads and spearheads, or armour fittings (from cuirasses, scabbards, belts, straps, or horse harness) are the objects most likely to be found on sites.

Armour varies in its prominence in the archaeological record. Plate armour would have been more susceptible to damage, even when not in use, and thus enter the archaeological record in scrap heaps of material waiting to be re-melted (in the case of copper-alloy fittings), or repaired. This could account for fewer finds of ring-mail (*lorica hamata*), as this type of armour has a lower attrition rate (Bishop 1989; 2011).

The same can be said about equine equipment, which consisted of mobile objects susceptible to becoming loose and lost, or suffer damage. Examples of this are the harness fittings from Longthorpe, which could have all been scrap material (Bishop 1989). Loss, damage and scrap material could account for an over-representation of these types of equipment in the archaeological record (Feugère 2002). An incorrect interpretation of the grave stone of Valerius Crispus led Lindenschmit (1881) to believe it depicted a soldier in leather armour. Today, the figure is considered to be wearing a typical *lorica hamata* from its time. D'Amato and Sumner (2009) have revived the discussion about leather armour in the Roman army, by mentioning the existence of leather strips from Qasr-Ibrahim, in Egypt and thus trying to build a case for the use of leather armour, which would not have survived in non-arid condition. Fischer (2012) disagreed, explaining they belong to the protective equipment of a charioteer. This opinion is supported by representational evidence such as terracotta figurines from Utica (Tunisia), which display protective equipment similar to that from Qasr-Ibrahim.

Researchers have found that finds of military equipment are not evenly distributed across time, with the majority of the military objects from the Roman Empire dating from the first centuries AD. When referring to a civilian context in southern Gaul (Clermont-l'Hérault, a *vicus* related to a road junction) for example, Feugère (2002) noted that the ratio of High Empire to Low Empire military finds was 4 to 1.

2.4.3 Typological , 'change' studies and specificity of equipment

As time passed, Roman military equipment grew to be very varied and reflected ethnic traditions (as weapons, helmets, armour and decoration demonstrate) from diverse cultural spheres of the Empire and its neighbours. The expansion of the Empire, stylistic traits, elements of identity, adaptation of tactics, and mobility of troops all contributed to this complexity and these factors were not mutually exclusive. Change was not a short-term conversion, but a gradual process in which the old types are only decades later definitively replaced by the new (Waurick 1989).

Assimilation of foreign traditions and tactics was normally favoured by the Roman army. Examples of this are numerous since the time of Caesar, when Gallic cavalry tactics were used against enemies (Goldsworthy 1996: 68), and mail armour, cavalry harnesses, saddles and Gallic helmets were imitated from 'Agen/Port' types (Connolly 1989). Other examples to consider are the Montefortino helmet, of Etrusco-Corinthian origin (Goldsworthy 2003) and the *gladius* and the *pugio*, which were Iberian contributions that became standards in the Roman army.

Roth (2009) exemplifies a linear and simplistic manner in which military equipment has been presented many times, as still-shots from each era that hide gradual and multi-directional evolution by presenting change in a linear way. Roth mentions some of the equipment that each soldier would have worn starting from that of a Greek hoplite, and how it changed over time. For example the *scutum* replacing the hoplite *clypeus* (Roth op. cit.: 22), the appearance of the *lorica segmentata* in the first century, and the return to scale armour (*lorica squamata*) or mail armour in the second century; or the adoption of the *spatha* for the short sword *gladius*. By the third century legionaries and auxiliaries increasingly wore similar equipment. In the late Empire trousers were introduced amongst cavalrymen, a broad belt was worn by every soldier and some conical helmets began to appear. The third century brought about the levelling of cavalry and infantry equipment as well, as all of them wore Intercisa type of helmets (Stephenson 2006).

A linear evolutionary approach can be expanded to form very complex classification systems for different time periods without actually addressing mechanisms of change. Typological studies that integrate documentary, representational and artefactual evidence (shape and function only) seem dominant when surveying the history of study of military equipment. There are even pieces of armour with no context that had been morphologically studied, such as the copper-alloy 'Ossorio' helmet (Bennett 1989). But normally these types of study offer very detailed and descriptive analysis of a huge variety of equipment. They include helmets, swords, lances, *pila*, darts, daggers, body armour, bows, and cavalry equipment, and a vast array of fittings, amongst many others, even studs (Aurrecoechea 1996).

Specific examples of typological studies are Bishop's (2002) classification of plate armour types (Kalkriese, Corbridge, Newstead, Alba Iulia) and cavalry fittings (Bishop 1988). Hawkes and Dunning (1961) and Böhme (1974) developed typologies of belt fittings, and Wild (1970) one of loop fasteners. Different typologies can be observed for spearheads and other iron weapons (Manning 1985). At Vechten, in the Netherlands, pieces of highly decorated helmets belonging to both cavalry and infantry (mainly iron), and fragments of the three types of body armour probably from the 2nd to 3rd century AD (mail, scale and plate), and horse armour (part of a chamfron) were found (Kalee 1989), the variation in helmet typology being noteworthy and included facemasks. Some of these objects present problems due to their variability. 'Leaf shaped spearheads', the most common type found in Britain, have in fact a wide range of measurements across the empire. Manning's typology of spearheads was based solely on material from Hod Hill, and this could be the reason his typology seems to separate successfully spears by distinctive groups (Marchant 1990).

There have been typological studies of helmets and change over time based on the archaeological record, which has added new dimensions for intercultural exchange and questions of ethnicity. However the usefulness of typological analysis has sometimes been compromised by over-classification. Helmets constitute an illustrative example on typological studies.

Helmets were initially described, classified and named according to the place where they were found and considered to have appeared and evolved in a linear chronological manner (Robinson 1975). The Republican Montefortino type helmet would have been succeeded by the Coolus type, and later the Imperial Gallic and Imperial Italic types, each with their sets of subtypes and variants, in a model that admitted little co-existence amongst the different kinds.

Different terminology in scholarship further complicates matters. A prime example is the different terminology used for helmets between German and British researchers. For instance, a Coolus type helmet roughly corresponds to a Hagenau in the German terminology. Similarly, Imperial Gallic and some of the Robinson's Imperial Italic helmets correspond to the Weisenau type, while other Imperial Italic types are seen as the Niederbieber type in Germany.

Fischer (2012) considered that Robinson's approach generated an excessive number of types (Montefortino, Imperial Gallic, Imperial Italic, and cavalry helmet types and their subclassification), often represented by very few examples or only one, a fact that made him state that classifications such as cavalry helmets, parade helmets, legionary helmets, and infantry helmets are all arbitrary. Fischer suggested a new typology close to that of Junkelmann, substituting subtypes for variants. Junkelmann's typology integrates other previous attempts by Couissin, Klumbach and Waurick (Couissin 1926; Klumbach 1974; Waurick 1988) for accommodating greater diversity of helmets and proposed the Montefortino, Mannheim, Hagenau and Weisenau as the main infantry types, and Weyler and Koblenz-Bubenheim as cavalry helmet main forms.

Roman swords are another example of equipment initially thought to have evolved in a linear way, and later seen as having changed in a multi-directional manner (James 2012). The *gladius hispaniensis,* a sword for thrusting copied from Iberian types actually evolved into many variants of two general types: the shorter and slender 'Mainz' type, and the even shorter and narrower 'Pompeii' type, which appeared later, by the 70s. Other types of swords co-existed with the 'Mainz' and 'Pompeii' *gladii* for a number of years, such as the 'Neoportus' and the 'Fontillet', probably having Gallic and Hispanic input in their development. The end of the first century AD saw the appearance of a longer sword, the *spatha,* coinciding with changes in the *lorica segmentata* and helmet neck guards, probably in connection with changes in fighting techniques, as protection focused on shoulders and neck during that century (Bishop & Coulston 2006; Bishop 2011).

Even though the evolution of equipment is not a linear phenomenon, changes in armour functionality and also in decorative styles of military equipment fittings can be clearly seen when a broad temporal and spatial scale are considered. For example, *gladii* are considered to have been used as thrust weapons fitted to a specific type of combat in a determined place, while helmets were modified according to the types of blow against which they could have been effective when fighting in definite body postures (Connolly 1991). In later periods, an emphasis was placed on protecting exposed limbs. This broad view is exemplified by the decades between AD130 and 190, which scholars have referred to as the `Antonine Revolution', noting how the equipment is markedly different to previous decades. Bishop and Coulston (1993; 2006) and Goldsworthy (1996) are more inclusive in writing that stylistic or cultural considerations are to be acknowledged as well.

Causes of change are not mutually exclusive and could have coexisted or, as Bishop and Coulston (1993: 203-4) put it, the evolution of Roman military equipment seems to have been driven by two factors: technical determinism and cultural change.

There is also information about the disappearance of specific equipment, like the absence of scabbards in the archaeological record in the fourth century (Southern & Dixon 1996: 99-105), or the marked decrease of dagger finds (*pugio)* in the 2nd century, and their return during the 3rd century. Other changes are explained either by an adopted technology, such as in the case of the Sassanid helmets that gave origin to the ´Type C´ helmet, changes in the size of the army forcing different production techniques, or internal variations and improvement in former designs (Stephenson 2006).

Cultural changes were recurring and continuous, especially as the army was based along the frontiers. Sometimes changes are very specific, such as the gradual shift from the double belt (for *gladius* and *pugio*) to a single belt during the first century AD (James 2012). Bishop (1987) has shown how units carried with them stylistic and decorative features in their equipment and how this equipment changed. In addition it was suggested that introducing variation could help to identify and track specific units. This model traced specific stylistic changes introduced in military fittings as specific legions moved from Pannonia and Germania to Britain in mid-first century AD (Bishop 1987). It was shown, for instance, that at Windisch (Vindonissa), Chester (Deva), and Budapest (Aquincum) similar stylistic features were found in different types of equipment. *Legio II Adiutrix* was at some point at each of these sites and so may be the reason for the presence of stylistically similar pieces of equipment. Particular forms of kit, whether in form or decoration might be identified as being specific to particular Roman military units ('specificity'), normally legions. For example, for 1st century AD equipment, some particular stylistic features (the size of lobate hinges, or the presence

of lobes in hinged plates) can be seen across different classes of *lorica segmentata* fittings of the Danube area that are not present in equipment from the Rhineland or Britain (Figure 2.1).

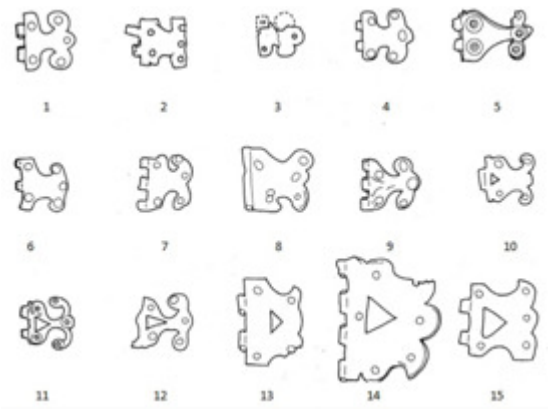


Fig 2.1a

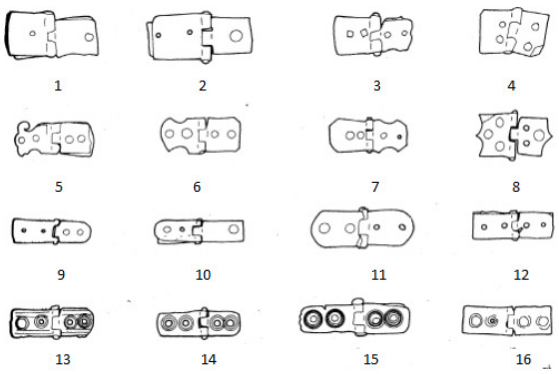


Fig 2.1b

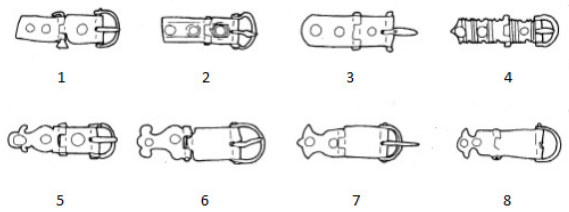


Fig.2.1c

Figure 2.1 *Lorica segmentata* fittings including examples from the Danube:, Fig. 2.1a 13-15, Fig. 2.1b 5-7 Fig. 2.1c 5-8 (from Bishop 1987).

Some types of equipment cannot be expected to be present in the archaeological record in the same quantities for some sites or regions; this is due to availability, local situation, or for tactical purposes. As an example, in Hadrianic Britain, the number of archer units would have been far less than in Cappadocia at the same time, since enemy tactics significantly differed between both regions (Goldsworthy 1996). This disparity in types of equipment could be caused by, or contributed to, the varying proportions of different types of units. For instance, by legionary- or auxiliary- specific equipment, in case there was any specificity. These variations appear to have only increased with time as the empire expanded and established contacts with different peoples, exchanging technology with them (Bishop & Coulston 2006: 270-72), up to the point when little or no differences are apparent between certain items of legionary or auxiliary equipment, such as swords or helmets (James 2012: 123). However, it is difficult to say how different auxiliary equipment could have been from its legionary counterpart. Arming auxiliaries in the same way as legionaries would have caused problems amongst the soldiers, though. Finding 'legionary' equipment at auxiliary forts

could mean that legionaries were present at some point or simply that scrap metal was needed to meet raw metal demand and transported there (Bishop 1986).

For Fischer (2012), in the light of the finds so far, helmets, armour, swords, and daggers could have all been used equally by legionary or auxiliary infantry, unless difference was expressed in textiles: any distinction could have been made apparent through colour, clothing decoration, or by the tunic or a cape. So far the only way it is known that legions distinguished themselves was by colours, symbols or markings on their shields: Tacitus wrote that in the civil war of AD69, troops used shields captured from the enemy to create confusion, which also suggests that the units were not readily identified by anything other than their shields (*Hist*. 3.23).

Helmets and shields (such as the hexagonal shield) are regarded as distinctive of auxiliary cavalry. Apparently, armour (*lorica hamata* and *squamata,* but not *segmentata*) did not differentiate infantry auxiliary units. In the early imperial period, the infantry probably carried a *spatha* and an undecorated belt and lacked daggers (Fischer 2012: 100).

For Deschler-Erb, it is not easy to tell the difference between military horse harness equipment and that of a beast of burden. He established three criteria to define military horse harness equipment (as reported by Fischer 2012: 217):

- When the objects can be identified by representational evidence
- When the finds are found in a context related to the military.
- When the design is widespread

To illustrate the complexity of specificity of certain items of the equipment of the Roman army, the example of Dacia is particularly useful. Legions were very active in Dacia during the first decade of the second century AD as the region was being conquered and the dominated territories consolidated. As mentioned above, in Rome legionaries were represented on Trajan's Column all wearing *lorica segmentata*. However, plate armour is scarce in the archaeological record for the region, and very little has been published. In contrast, scale armour has been found at several sites (auxiliary forts) in both the initial and later period of consolidation after the conquest. It would seem that both legionaries and auxiliaries were using mainly *lorica squamata* (Dawson 1989).

2.5 Reconstruction studies

Attempts at reconstructing Roman military equipment are not uncommon and range from pictorial representations to full-sized tangible replicas and experiments to test them.

There have been descriptions and reconstruction by drawings of short swords, *spathae*, hilts daggers shafted weapons, axes, bows, arrows, quivers, clothing, standards, buckles and fittings from belts, and decorations. We can see geometrical descriptions of shields, measurement of thickness, and how they were painted for identification during battle (Southern & Dixon 1996). The size of some of these shields has been hypothesised by the finding of fragments of a leather cover at Caerleon (van Driel-Murray 1988), but also by shield fragments from Masada (Stiebel & Magness 2007), and Dura-Europos (James 2004).

Some groups of researchers have undertaken reconstructions of military equipment and sometimes have even tested them to assess their performance, but mainly for understanding how a particular item worked.

As examples we have the case of plate armour, types of which have undergone several reconstruction attempts by von Groller (in 1901, based on Trajan's Column), Robinson (1975), Connolly (in Allason-Jones & Bishop 1988, Figs. 23-4), Poulter and Turner (Poulter 1988) and Bishop (2002). Poulter assessed an attempted reconstruction of a 2nd century AD *lorica segmentata* by Robinson from the site of Newstead. While based on a different type of plate armour, the Corbridge type, the reconstruction had its problems, such as sharp edges along the neck, and that the soldier would not have been able to put it on unassisted. Later Bishop offered a successfully functional reconstruction of the Newstead variant (Bishop 2002). Alternative reconstruction possibilities for different types of *loricae* have been suggested by Travis and Travis (2012).

Compositional and processing differences between ancient and modern metals employed in reconstruction studies are likely to significantly affect results and the conclusions derived from them. Goldsworthy (2003) reports tests of the maximum range for *pila* to be effective (to have sufficient penetrative power to pass through a shield). This probably should be taken with some reservations. Since two fundamental components of a *pilum* were made of ferrous alloys, these tests are probably not very accurate even if the functional principles are correct. This is because there are differences in composition (and processes that could introduce porosities or inclusions, for example) between the alloys used by the Romans and those made for the reconstruction and testing. These would result in significant differences in experimental outcomes.

Other studies have addressed the behaviour of military equipment of soldiers dressed in full kit. Experiments carried out in Holland, involving re-enactors marching for two and four days covering distances of 52 and 100 miles, respectively, and being fully dressed in Roman military equipment (four as legionaries and a light auxiliary from the 1st century, and two infantrymen wearing equipment from the 4th century) assessed the effects on the equipment and soldiers.

Amongst the results it was found that the metal of the *lorica segmentata* required the application of grease to avoid corrosion under perspiration, and that carrying the helmet in the manner suggested on Trajan's Column (from the shoulder plates), caused the fracture of the pin of a cheekpiece (Atkinson & Morgan 1987).

Analogies with other time periods are sometimes used to aid reconstruction, such as using medieval-style padding under reconstructed armour, as it is thought that the garment probably protected the wearer from the friction of the armour, as well as adding some additional protection (Stephenson 2006: 62). Ethnographic sources work in the same way. A clear example is assessing the effectiveness of slings as weapons and a possible decline in use through ethnographic parallels of construction and assessing performance (in Mongolia). This information, being with the documentary evidence from classical writers, resulted in a possible way in which slings could have been used, evaluating their range and accuracy (Griffiths 1989).

Anstee (1953) wrote about a possible way in which scale armour from Corbridge could have been manufactured. More recently, Sim and Kaminski (2012) offered an experimental study of how ferrous Roman imperial armour could have been produced, detailing extant blacksmithing and manufacturing techniques that are likely to have been used to fabricate scales, helmets, ring mail, plate armour and shield bosses and edging. However, the material chosen for this reconstructive process was mild-steel, whose performance would differ from ancient alloys, both during production and in its working life.

2.6 Producers and supply

The Roman army's military equipment supply seems to have varied in scale over time and across the empire. There are antecedents in Republican times for both outsourcing from private contractors to produce military equipment and the army producing their own equipment, as objects interpreted to be greave presses (to form greaves from metal sheet, probably for mass production) found in Cáceres, Spain, suggest (Bishop & Coulston 2006: 64).

There is written evidence of small forts (on the Vindolanda Tablets 597 and 852) dealing with daily work done in a *fabrica*, where metalworking and repairs took place (Grønlund Evers 2011), and in Egypt, a papyrus dating probably from the 2nd or 3rd century AD accounts for 100 men of *legio II Traiana Fortis* engaged in the production of *spathae*, two types of shields, iron plates, bows, and catapult fittings, with some items made in the *fabrica* and some others that were only completed there (Bishop 1985a). Later literary evidence comes from the *Notitia Dignitatum*, but it provides

information about centralised production during the 4th century, and it pertains only to the late Empire (James 1988).

The Luguvalium Tablet 16 from Carlisle and the Vindolanda Tablet 861 seem to show two different types of spear supply to their garrisons. In the tablet from Carlisle, Dociles writes to his prefect Augurinus asking for lances for specific soldiers and thus suggesting that soldiers acquired these weapons through a command structure within the army. In contrast, the Vindolanda Tablet suggests spears being sold to soldiers probably by contractors (Grønlund Evers 2011*)*. It seems that there could have been variations in the type of supply co-existing depending on the importance of the fort, that is, either through official channels within the army or through external contractors.

Archaeological evidence, such as broken and cut pieces of metal, failed castings and moulds found at forts and *vici* suggests that not only repair, but production of equipment was carried out at least in some forts. Small private manufacturers could have produced military equipment amongst other metal objects (Oldenstein 1985). Oldenstein did not think that *fabricae* within forts were able to equip fully garrisoned units, this being unnecessary as new units arrived with their own equipment already. This would mean that the function of local *fabricae* was mainly repairing equipment. Even the moulds found could be considered as repairing tools, if they worked to complete broken equipment from an available model. Still, *fabricae* at the fortresses in Exeter and Inchtuthil, both in Britain, may indicate that industrial activities were carried out on a great scale, if judged by the dimensions of the *fabricae,* as that from Inchtuthil measured 58.5m by 59.7m, and in Exeter a lathe, a smithy and a work bench seem to have existed (Bidwell 2007: 108).

Besides Inchtuthil (Victoria) and Vindolanda, other probable *fabricae* from the first and second centuries AD have been identified, amongst which York, Nijmegen, Nicopolis (Egypt), Hunerberg, Haltern, Hofheim, Valkenburg, Oberstimm, Bonn (*Germania inferior*), Moosberg (*Raetia*), Niederbieber, Rheingönheim, Wiesbaden (*Germania superior*), or Corbridge in the third century are examples. Their existence can be suggested by finds of leatherworking and metalworking evidence, waste products, or raw materials (Bishop 1985a; James 2012).

In Roman military equipment studies two similar views were developed regarding production of equipment (Bishop 1985a). In 1960 MacMullen wrote that most of the equipment was produced by small shops. Robinson (1975) suggested that the army could have repaired and maintained their own equipment, or fabricated it in times of emergency, and any average workshop could have produced items like javelin heads, or arrows, but it was private firms that normally produced the equipment. The picture seems to be more complex, perhaps involving a mixture of local and

centralised production depending on geography and specific moments or emergencies, and also on the type of item being manufactured.

Oldenstein (1985) argued that the fact that there are similar military objects in geographically separated regions across the Roman army did not mean that the equipment was centrally produced, but that models were copied at a local production level, whatever the scale of production. For Oldenstein, the evidence is against a state monopoly in military equipment production for the first three centuries AD. New units were not frequent and equipping them could have happened every 10 years on average, and it was only when sudden demand peaks appeared, such as civil wars, that equipment could have been produced in cities inside the empire and not in their provinces.

Sommer (1991) has suggested that settlements and forts appeared simultaneously as people followed the camps, and civilians followed their units to their new stations. Sommer (1989) also believed that the people from the *vici* were originally from where the unit was raised and that almost every *vicus* had its own pottery production and/or metal-working, an example being the *canabae* outside the legionary fortress of Caerleon, where evidence of iron-smelting was found (Brewer 2002a). At South Shields, ring-mail was apparently being made in one of the *contubernia* of the cavalry unit in Antonine times, and a manufacturing centre at Holt or at Wilderspool probably supplied *legio XX* at Chester. Other manufacturing sites, at Grimescar, Brampton, Muncaster and Walton-le-Dale, probably supplied auxiliary units at nearby forts (Bidwell 2007: 109-10).

Sheepen (Colchester) probably supplied the nearby legionary fortress (Niblett 1985) during the early occupation of Britain. Although *legio XX Valeria Victrix*, the unit garrisoned there, left in AD49, metallurgical activities seemed to have continued since some crucibles and moulds found there belong to the following period when a *colonia* was established (AD49-60; Niblett op. cit.). This could suggest that supply to the army continued, but could also mean that copper alloy was melted to produce non-military materials.

It is important to state that different technological operations in the life cycle of military equipment, such as component productions, assembly, repair, and recycling are unlikely to have taken place in the same location. Besides production of the equipment itself, there is the problem of where the metal was mined and smelted. Evidence of melting, but not of smelting is found as well in north-western European forts. As an example, in one corner of the fort of Oudenburg (Belgium) workshops from the late third century were found, including several hearths and two furnaces (Vanhoutte 2009). In addition to the furnaces, evidence of metal working was obtained in the form of some finished, unfinished or waste products, and metal slag. In particular, brooches and brooch elements that indicate different stages in the brooch manufacturing process were present. A large

number of objects (of copper alloy and iron), including hundreds of coins of varying sizes, were found associated with the burnt remains of a workshop, and could have been used as scrap material. The furnaces could have been used both for ferrous and non-ferrous metalworking, and there's evidence of copper-alloy casting, as x-ray photography on blocks of soil show drips of metal within. It is likely that the furnaces were used for melting and heating for hammering or working.

There are traces of brass in the inner surfaces of crucibles found at Sheepen (Niblett 1985), which were identified with x-ray fluorescence, meaning that brass or gunmetal was being cast. However there is no evidence of copper smelting. Also at Sheepen a brass ingot was found in a pre-Boudiccan rubbish pit bearing an inscription: VHETB (Collingwood & Wright 1990, RIB 2407), but its provenance is not known.

Evidence for the production of small copper-alloy objects was found at Housesteads, in a corner of the fort that could have been a workshop built into the rampart (Dungworth & Starley 2009). Three mould fragments for seemingly identical belt buckles were found, along with crucibles and slag associated with casting. Scrap metal off-cuts and droplets were also recovered.

Theories about itinerant craftsmen have been proposed to explain almost identical objects found in separate regions, as in the case of a stud from Gilau (Romania) bearing the head of a *genius,* and an almost identical one (looking to the opposite direction) from Mainz Museum. However they could equally have been produced by a specific production centre (Diaconescu & Opreanu 1987).

Bishop (1985a) has suggested that craftsmen in frontier regions were not subject to central control. This probability and the high mobility of troops in these regions would have constituted a situation that would account for the variety shown by the equipment in these areas, as these craftsmen could have started from basic design features and then changed some of them according to soldiers' wishes or theirs. Some items would be more likely to display this type of variation, such as belt-plates, scabbards, straps, aprons, or even armour fittings (*lorica segmentata)*.

Bishop (1992), when discussing early imperial aprons, argued that the range of variation found in them, and considering their limited function, could be related to individuality within units; reflecting a loose production system. Oldenstein (1976) considered that minor objects like fittings and pendants were locally produced and any similarity should be explained as fashion. However, some objects, such as horse-harness fittings, are distributed in a very wide scale.

Alesia (Gaul) could have been a centre for the mass-production of horse-harness equipment as moulds for pendants and fittings found there suggest. Alesia could have been a centre for specialised

manufacturing serving a vast region. Most of the objects are made of brass and generally silvered and niello (a silver or copper sulphide [La Niece 1983]) inlaid. They were probably produced between AD 50 and 60. Parallels are found in other sites between AD 60 and 80 in Britain, France, Germany, and the Netherlands (Rabeisen 1990), suggesting Alesia as a possible source of the equipment, or at least a stylistic model.

Typological differences do not necessarily mean production in different workshops. In the case of a certain copper-alloy belt stud, the existence of a central source has been suggested in Besançon (from Nero to Trajan), where gifts were produced to reward legionaries on different occasions. Such a unique place of production would have been important as these studs were similar to coins in their propagandistic nature, their stamped heads having to meet specific iconographic requirements (Feugère 1985).

Oldenstein (1985) has identified three phases for the procurement of equipment in new provinces, such as Britain, and links those phases with methods and places of production in an effort to summarise equipment production in the Imperial period:

- First, the conquest phase, when the army needed to be supplied by the continent, exemplified by elaborate and specialised large scale manufacturing (such as the silvered and niello inlaid heart-shaped harness pendants of the Claudian/Neronian period).
- A second phase of transition (from the Neronian to Flavian period), where local production was able to satisfy the needs of the largest units (with less decorated harness pendants imitating those of the previous phase); and
- A third phase, of near self-sufficiency of production.
- Following these three phases, by the fourth century AD, private industries were unable to meet the requirements of the army, resulting in the state assuming control on general production.

In the eastern provinces of the empire, supply was traditionally associated with the old Hellenistic city-states that were able to quickly produce large quantities of equipment (Bishop 1985a). In the western provinces armies were not based near cities with long established industries and needed a higher degree of sufficiency (Bishop & Coulston 2006: 238).

The lifespan of certain objects represents a problem for dating, since they can be passed hand to hand before being lost, or repaired, as can be seen in some elaborate fittings from Carlisle (Howard-Davis 2009), but they could also be indicative of the place of production. At least some types of equipment, such as sword scabbards, could be supplied by private workshops (instances of

inscriptions on scabbards with the name of Quintus Nonienus Pudes from Cologne, for example), or others fabricating swords and shields (Oldenstein 1985). Dagger scabbards, for example, could have had very extended lifetimes, as they were generally costly and durable. This makes dating and a potential identification of the place of production very difficult. However their successors were wooden ones, having metal only in the form of attached plates. This could be related to a change to centralised production by the army. Wooden dagger sheaths with metallic plates succeeded metallic scabbards and were in use for longer. These simpler scabbards could have been linked to a possible relative centralisation of production managed by the army, with Strasbourg or Lyon supplying the Upper Rhine, for example, due to a change in the mobility of the army, as large scale campaigns and territorial expansion slowed under Nero (Scott 1985).

2.7 Ownership

Ownership and production of military equipment are concepts prone to be correlated. For example, individual ownership of equipment could favour local procurement and this, in turn, local production.

The typology of helmets illustrates changes in production during the late Republic and early Empire (Paddock 1985). It is clear that during the Republican period soldiers owned their equipment and had to procure it themselves. The Civil and Social Wars and the reforms of Marius of the first century BC caused this situation to change and helmets began to be mass-produced to satisfy an increasing demand. This is attested by helmets bearing the stamps of the maker, but accompanied with a significant drop in quality. Helmet production changed once again with the reforms of Augustus in 25BC and helmets were then produced by spinning, instead of being beaten to shape, thus increasing production quality and output. However, the need for production could have been low at least for some types of equipment, which were probably used as scrap metal after being used by the last owner, or given to the army after retirement or death and exchanged for money, and needing only repair to be fit for use (Bishop 1985a). It is probable that workshops employed most of their time in repair, rather than producing new equipment (Bishop 2011).

Gilliam (1967) and Speidel (1992) wrote about the availability of equipment according to the writings in Egyptian papyri, and concluded that weapons of deceased auxiliary soldiers were purchased by the unit and the money was given to the soldier's mother; soldiers who ended their service could sell their weapons to the *custos armorum* in the unit and then sold on to new recruits, individual troops could buy their equipment by instalments or in one transaction (or pawn a second set), or could ask for relatives to send them weapons and clothes (Fischer 2012).

The lifespan of some types of military equipment allowed for several owners. Coolus type helmets found at Xanten, probably in connection with the Batavian Revolt of AD69 (Fischer 2012), had been traditionally thought to have been replaced by the Imperial Gallic type long before. Proof of ownership can be direct in the case of some of these objects. For instance, a set of horse trappings, also from Xanten, has two soldier names punched on the back of the objects (Jenkins *et al* 1985). An Imperial Gallic helmet from the Guttmann collection (as attested by multiple name inscriptions on the neck guard), could have had up to five different owners in the space of 100 years. A scabbard from Bingerbrück was still in use after 50 years (Fischer 2012).

The presence of equipment in graves, as mentioned above, increased with the number of soldiers from Germany, suggesting that the equipment was owned by the soldier. Equipment found in civilian contexts could point to veterans having lived there following retirement, with their equipment or at least part of it. The widespread distribution of military equipment in the towns of Britain, mainly dating the 2nd and 3rd centuries (with Colchester as an example), could be explained by the presence of veterans, but it also could mean the garrisoning of cities, or troops performing policing duties, or the private manufacturing of equipment, as the unfinished belt plate in Cirencester suggests (Bishop 1991; Fischer 2012).

The increase in the number of units and post-disaster situations, disrupted production and distribution networks of equipment in mid 3rd century AD, making it scarce. This situation could have prompted the creation of the *fabricae* during the time of Diocletian (Coulston 1990).

In Late Antiquity the majority of the weapons were clearly manufactured in specialised *fabricae* (as can be seen in the *Notitia Dignitatum*), but there is no evidence that all the equipment belonged to the state, and inscriptions with both unit (e.g. on shield bosses) and individual names (e.g. the Deurne helmet) can still be found (Fischer 2012), suggesting private ownership.

A letter dated AD401 authorised the discharge of 11 members from an *ala* stationed at Psofithis in Egypt, in which the prefect of the camp had to make sure that the soldiers returned the equipment they had used (Woods 1993). However, it is unknown if this was a general policy or not. A different case is presented in a hagiographical source, the *Passio Typassii*, c.AD397, featuring a veteran who kept his equipment in a store room at home and was later called back during a period of conscription, implying soldiers retired with their military equipment. Even if some aspects of military life and the terminology employed in the text could suggest that the author was knowledgeable in military matters, the military equipment being in a store room could be a symbol of an abandoned way of life from an early Christian perspective (Woods op.cit.: 57). Alternatively, ownership may have depended on rank or unit type.

2.8 Identification, identity and personalisation

For Webster (1985a), there was never a concept of uniformity in military equipment, except for probably the type of armour between types of units. When comparing decorated scabbards from Britain, Webster entertained the possibility of identifying patterns belonging to each legion. However, no relationship between decoration type and legion was found, the differences in design and degree of quality being explained rather by the period of time within which they were made (those richer coming from pre-Flavian times), or by the amount of money that each soldier was willing to pay to the craftsman who made them.

Gilliver (2007) has noted the awareness of the value of display and its psychological effects in the ancient world (cohesion within ranks and intimidating the enemy), including battlefield environments, expressed in colour, lustrous shine and sounds. Highly decorated equipment did not necessarily belong to high ranks, and soldiers would have gone to battle with their *insigniae*. The prospect of being recognised as outstanding for bravery could have taken precedence over the danger of being spotted as an easier target.

There are several elements that could have been related to identification in the battlefield; such as decoration on saddle plates, helmet crests and plumes (Bishop 2011), shield paint, or aprons (Bishop 1992). For instance, *legio* V was called '*Alaudae'* (*'The Larks'*) because its members wore side-plumes that resembled the feathers of a shore lark (Bishop 1990).

Perception and definitions of colour in antiquity were particular. The Greek concept of colour, for example, had to do more with luminosity, texture and contrast than with hue (Bradley 2009: 17).´ Cicero wrote about the unreliability of perception arguing that perception and knowledge are very different concepts and according to Seneca colours rely on an observer to exist and are manipulated by movement (Bradley op. cit: 412; 114). Terminology of colours is not easy to translate into modern vocabulary. The Latin colour term *flauus* is of difficult explanation but it could mean 'blond', 'yellow', and was sometimes associated with gold as *flauum aurum* ('yellow gold') or describing coins as *flaua moneta* (Bradley 2009: 3-5). Colour was used in military display as a means of association and identification (Gilliver 2007: 5).

Petculescu (1974-75) has argued that what has been considered as 'parade' armour, such as mail armour decorated with copper-alloy rings, *lorica* chest-pieces or helmets, was actually for practical use on the field. The armour would still have given effective protection in combat (Coulston 1990).

Soldiers traditionally wear belts in all representational sources, whether they are auxiliaries or legionaries (Ubl 1989). By the time of the late Empire, the adoption of the military belt as badge of office servants was widely spread, but it is possible that there were minor differences between the *cingulum* of the soldier and that of the civilian (Bishop 1991). Some fittings like apron terminals with pendants (used during the first centuries of the principate), announced the presence of a soldier with their jingling sound.

Military equipment could therefore be ostentatious, even if it did not necessarily belong to high ranking soldier (James 2012: 122), such as the 'Tiberius sword', with its plated scabbard, originally thought to have been silvered but later found it had been only tinned. Similarly, other tin plated fittings could have been intended to look like silver.

The Romans seemed to have had a preference for bright metallic surfaces of golden or silver appearance for purposes of show or intimidation, attested by the multiple kinds of plating found in all kinds of equipment or by the use of specific metals. These choices could override practical considerations, such as the bimetallic combination used in the *lorica segmentata* plates and fittings, (iron and brass), as two adjacent surfaces of different metals would promote corrosion on one of them. In this case the iron would corrode in preference to the brass (Oldfield 1988).

2.9 Recycling

Bishop and Coulston (2006: 234; Bishop 1991) link one of the main ways of entry of Roman military equipment into the archaeological record, as scrap material kept aside to be recycled, to the role of the army in equipment production, along with crucibles, tools, ingots, and unfinished equipment being found in military camps.

Scrap material must have been an important resource within forts. The cost of repair could have been absorbed by the soldier, and thus there could have been an incentive to retain and amass scrap material (Bishop 1985a). Damaged equipment, such as *lorica segmentata* fittings (apparently very prone to suffer damage) in Britain or north-west Germany found together in forts may have been part of a body or 'core hoard' of recycling material that the unit could take when it moved (Bishop 1985a; 1986).

Recycling equipment also includes reutilization without re-melting the metal of parts of weapons or armour, called by Bishop and Howard-Davis (2009) 'cannibalisation'. Fischer (2012: 84) provides examples: a brass plate from a dagger scabbard from Xanten, originally enamelled, was flipped over, decorated again, and then silvered; a brass sheet used as shield binding reutilised

either as part of a scabbard or a *lorica segmentata* fitting (found at Krefeld-Gellep): or reutilisation of equipment outside military contexts, such as decorated greaves used as box fittings in Regensburg.Metal recycling has important implications for any intended provenance analysis back to ore sources, as re-melting through extensive recycling would render chemical fingerprinting impossible, since it affects most elements within the melt (Pernicka 1999).

2.10 Metal Production

2.10.1 Copper

2.10.1.1 Sources and ores

The presence of imperial officers, and Roman army personnel at a site where extractive metallurgy operations were conducted points to imperial control (Hirt 2010). But the management of Roman mines was complex. Mines could be public, belong to cities or provincial governments, or to individuals, where emperors could be considered as well (Domergue 2008).

Some mines were directly operated and managed by the state, such as those of north-west Spain, for example Las Médulas (Domergue 2008: 200-1).The state could also give mines as concessions for individuals, or *conductores*, to work (as numerous scholars think is the case at Vipasca, Lusitania), but controlled by a procurator who claimed half of the yield. Lessees could share the rights to exploit a mine forming *societates* (Healy 1978). In Britain, for example, lead ingots in the Mendips, Shropshire, Flintshire, Derbyshire and Yorkshire have the names of emperors on them, from Nero to Severus (Domergue 2008: 191). However, these ingots do not necessarily indicate state ownership or a concession of the mines. Recent scholarship suggests that mining plots were sold at Vipasca to interested parties, where it is traditionally thought that only concessions were given (Hirt 2010). The main sources of copper in the west during Roman times (Healy 1978; Domergue 2008; Hirt 2010) were located as follows:

- In the Iberian peninsula in *Hispania Baetica* (Huelva, Cordoba),*Hispania Tarraconensis, and Lusitania:* with specific mines such as Turdetania (Rio Tinto), *Metallum Vipascense*, Cabezas del Pasto, Sotiel Coronada, Cotinae, Alentejo and from the first half of the first century AD: Serra da Caveira, San Domingos, Cerro Muriano, Córdoba, Asturias, and Lérida.
- In Gaul: in *Gallia Narbonensis*: Bastide de Serou (Ariege), La Roussignole, Mougno, Pioch - Farrus (Cabrières), and Lascours (L'Orb); in *Gallia Aquitania:* Banca
- In Britain: in Cheshire at Alderley Edge, north Wales (Anglesey at Parys Mountain, south of Amlwch); Llanymynech in the second and fourth centuries AD; Pentre, in south Wales

(starting before AD100), and possibly the Great Orme (Caernarvonshire) in the third and fourth centuries AD.

Our knowledge of ancient copper metallurgy is primarily based on the Bronze Age techniques found in the Near East, at sites such as the Wadi Arabah in the Negev, Timna in Israel or Faynan in Jordan, where there are also heaps of slag, evidencing Roman smelting (Hauptmann 2007: 307).

Copper ores containing about 1% copper can be smelted economically today, but in antiquity richer ores needed to be used, probably containing between 10 and 20% copper. The remaining 80 to 90% is called gangue and has to be removed as slag in the smelting process. The gangue often contains high amounts of silica or iron oxide. In the first case iron or manganese oxides are added as flux, while in the second case silica is added in the form of sand. Either way the objective is to form olivine type of compounds, $2FeOSiO_2$, which are not dissolved in copper easily and have a lower density than metallic copper (which therefore sinks to the bottom of the furnace), constituting slag. This slag can be then tapped off the furnace as a molten waste product that then solidifies outside the furnace and is discarded (Tylecote 1977).

Merkel (1990) experimented with smelting techniques based on Late Bronze Age and Iron Age material found at Timna by varying different parameters in the production process, such as furnace lining materials (stone vs. sand), number and position of tuyères, quantity and ratio of copper ore to fuel and flux, and airflow rates. The reconstructed processes achieved good compositional agreement between experimental tapped slag and archaeological slag.

2.10.1.2 The smelting process

First, the copper ore had to be manually sorted to select the material with the nodules richest in copper, a process called beneficiation. This process was essential to establish a recipe for ore to flux ratio and was achieved by crushing the ore and picking out the brightly coloured copper-rich minerals (such as malachite).

The smelting process, which consists of extracting metallic copper (by the reduction reaction) from its most stable condition in nature (in the form of compounds such as copper carbonates or oxides in ores), was carried out either in shaft or in bowl furnaces. The latter were essentially depressions in the ground covered with a clay lining, in which a charge of charcoal and ore was added. In this way the necessary components to provide fuel and a reducing environment were included. Air was provided via bellows, equipped with clay tuyères, which are ceramic tubes

that transmit the strong blast of air coming into a furnace, thus increasing the heat provided by the charcoal, as combustion is enhanced.

The fuel used was usually charcoal, produced by charring seasoned wood in a clamp kiln in the absence of oxygen. The result is carbon with ash with high calorific value and reducing capabilities. Selection of the wood is important, as the ash contained in charcoal acts as a flux during the smelting process and is incorporated into the slag.

Shaft furnaces were a later development (ubiquitous by the Roman period) and consisted of a vertical shaft of clay and/or stone supported by a wall, providing structure and insulation. The lower part of the shaft furnace was equipped with tuyères and an opening for tapping out the slag. The shaft furnace would be pre-heated and the charge (consisting of alternate layers of charcoal and a combination of ore and flux) would be added continuously until the tuyères blocked with slag (Merkel 1990). Then, the slag was tapped out and 'black copper', the products of the smelting process, remained in the base of the furnace. As mentioned above, the slags resulting from the smelting process are artificial minerals composed of ferrous silicates with high iron contents and low proportions of non-ferrous metals (Tylecote 1992).

Conditions within the furnace could have been monitored by observing the colours of flames produced by the hot gases (Merkel 1990), since a blue flame would have indicated excess fuel produced by a very reducing atmosphere (which needed to be controlled to prevent an excess of iron being produced), which would negatively affect the efficiency of the copper reduction process.

The most important chemical reactions at this stage are related to fuel combustion, smelting and slag formation (Merkel 1990):

For combustion:

$C + O_2 \rightarrow CO_2$

$C + CO_2 \rightarrow 2CO$

Copper oxides and copper carbonate reactions:

$CuCO_3 \cdot Cu(OH)_2 \rightarrow 2CuO + CO_2 + H_2O$

$2CuO \rightarrow Cu_2O + \frac{1}{2} O_2$

$Cu_2O + CO \rightarrow 2Cu + CO_2$

Flux reaction:

$Fe_2O_3 + CO \rightarrow 2FeO + CO_2$

Gangue reactions:

$SiO_2 + 2FeO \rightarrow 2FeOSiO_2$ (fayalite smelting slag)

$FeO + CO \rightarrow Fe + CO_2$

Another aspect which needed control was slag viscosity, since a high value would have inhibited the separation between the slag and the molten copper (Merkel 1990). Viscosity can be regulated by changing the ore to flux ratio, increasing the amount of flux material. For example, if the slag was too viscous, more flux could be added so that it could be more easily tapped out.

Smelting experiments conducted by Merkel (1990) show an initial efficiency (which depends on ore grade, airflow and slag composition) of 50-60% in the smelting process, but this value could be increased by manually sorting copper-rich furnace slag and then recharging the copper prills obtained.

The end product is a copper that is high in iron, most of it coming from the flux introduced in the smelting charge. Following smelting, the copper was refined to get rid of the iron; a process which involved re-melting the smelted copper and obtaining slag again as a sub-product, called crucible slag. Refining removes most impurities in the copper product, including most of the excess iron. Deliberate fire refining by heating in the presence of charcoal, ash and silica produces a slag that removes the iron to trace levels, but even one cycle of re-melting in air significantly removes the iron (about 80%), and the effect could have been enhanced by repeated re-melting (Merkel 1990). Simple re-melting allows the iron in the copper to oxidise and form a slag that can be scraped-off the molten copper. The melting of metal requires far less energy than the smelting and decomposition of malachite to cuprite and its reduction to metal (Hauptman 2007).

Crucible slags tend to have low contents of iron and high levels of non-ferrous metals. The resulting refined copper was subsequently cast into plano-convex ingots, which could weigh as much as 20kg. A temperature of over 1200°C is needed to cast copper, since at least 20°C superheat over its melting point is needed (Tylecote 1992).

The main chemical reactions during the refining process are (Merkel 1990):

$2Fe + O_2 \rightarrow 2FeO$

$2FeO + SiO_2 \rightarrow 2FeO \cdot SiO_2$ (fayalite crucible slag)

$CuO + CO \rightarrow Cu + CO_2$

Simple sulphidic ores require an additional process called roasting to make smelting possible. This stage converts sulphides into oxides by heating, removing some trace elements as

well, resulting in a generally purer copper after smelting when compared to a non-sulphidic (oxide or carbonate) ore.

An alternative form of obtaining metallic copper from more complex sulphidic ores requires a special process called 'matte smelting', a two-staged smelting process (Tylecote 1992). After an initial partial roasting, the ores need to be smelted first in the presence of a flux, so that the 'matte', a mixture of copper and iron sulphide compounds, is obtained. Once matte is obtained, it is roasted to obtain oxidised matte, which could then be reduced to metallic copper during the second smelting stage. The product could then be refined by re-melting.

2.10.2 Bronze

According to the ancient authors Diodorus and Polybius, *Belerium* (Cornwall) was a source of tin in the first millennium BC (Davies 1935: 142-3). The ore was smelted and cast into *astragali* (ankle bone) shaped ingots. Later, the conquest of the Iberian Peninsula made it possible to exploit tin ores from Lusitania, Galicia and Turdetania (Rio Tinto) in Spain (Healy 1978).

Bronze is the alloy of copper and tin, and could have been made in two possible ways (Tylecote 1992). The first involves heating copper and tin ore (such as cassiterite) together in a reducing atmosphere (under charcoal, for example) and heating it to the melting point of bronze (which depends on the amount of tin in the copper). Alternatively bronze can be produced by directly adding tin to molten copper. This process requires a furnace with bellows and a crucible, where the copper ingot and the alloying elements (such as tin or lead) are added, and no reducing conditions are needed, since the tin ore would have undergone its own smelting process from its mineral, a process which requires a temperature around 1000°C . Roman purse-shaped tin ingots are known, for example those produced in Spain and found in the Mediterranean (Tylecote 1986) and (arguably) those from Devon (Fox 1996).

2.10.3 Brass

2.10.3.1 Brass and the Romans

Brass is the alloy of copper and zinc and is especially important in Roman military equipment from the first two centuries AD.

Deliberate production of brass probably started amongst the Phrygians in Asia Minor in the first half of the first millennium BC, and apparently was not replicated in any other place before the

Hellenistic period. For instance no European group of Bronze Age metalwork from a hoard has shown anything more than traces of zinc, strongly suggesting that its makers were unaware of its presence (Craddock 1978). The earliest mention of brass in literature is from the 7th century BC, where it is called *oreichalkos* (or 'copper of the mountain') presumably referring to the source of specific poly-metallic ores containing both zinc and copper. At this time brass was a very expensive material, as it could only be fabricated by a very inefficient process mentioned in the *Philippica* of Theopompus, written in the 4th century BC (Craddock 1978).

Brass was first seen as just another type of copper, even if rare, produced with a very specific poly-metallic ore (Martinón Torres & Rehren 2008b). At this stage it probably was 'natural brass' or brass produced by smelting particular and scarce copper ores rich in zinc, which would later be explained by Pliny's comments about the exhaustion of certain ore (Craddock 1995: 295-6).

It was not until the first century BC that brass was artificially produced on a larger scale, first in Asia Minor and then taken up by the Romans to even larger quantities. Coins of Mithradates VI, king of Pontus, are the earliest closely dated pieces, being from the early first century BC (Hook & Craddock 1996). Some brass artefacts could have been made from Roman coins: brass artefacts (produced after 45BC) from the Titelberg (the site of a large *oppidum* in Luxemburg, probably coming from Asia Minor (Galatia) too (Hamilton 1996) as well as Herodian brasses from Jerusalem, dated to the second half of the first century BC (Ponting 2006).

Istenič and Šmit (2007) analysed several pre-Augustan brooches from the south-eastern Alpine region of Slovenia. Some military brooches were found to have been made of brass, such as Roman 'Alesia' type brooches, dated from 58/51 to 44BC. Outside of the assumed Roman brooches in their study, no brass was found. The authors report more evidence to link the Romans to early brass use in Europe, as some coins from the Arverni tribe in central-southern Gaul, dating probably from the Roman siege of 52BC, contained 10-15% brass, which was assumed to have been recycled from Roman objects and used as a substitute for gold due to its colour. This study draws important conclusions, such as brass being first used for military equipment and military brooches before being used in coins (in a coin issue of 46/45BC), and presents an argument in favour of the Romans introducing brass technology into Europe. According to Hamilton (1996), Belgic Gaul and the Roman Republic/Empire acquired the knowledge of cementation brass independently from Asia Minor, the people of the Treveran area working with brass earlier than the Romans. Istenič and Šmit (op. cit.) question these conclusions stating that the brass objects reported by Hamilton were in fact of Roman origin and of questionable date.

The Romans produced brass coins (*dupondii* and *sestertii*) on a larger scale following the general reform of 23BC and brass continued to be used for military fittings, as in the case of a late 1st century BC scabbard plate from the River Ljubljanica in Slovenia (Šmit *et al* 2010). Later other small objects, such as lamps, were made at the expense of bronze (Hook & Craddock 1996), so that brass appears to be considered as a cultural marker during the Roman period. It was now called *aurichalcum*, making reference to its golden colour, and produced with a much more controlled and efficient process, as described by Pliny (*Naturalis historiae* 34.2.2*)* in the first century AD (Craddock 1978).

However correct the identification of brass making with the Romans is, it does not mean that brass was not known in Britain prior to the arrival of the Romans. There is evidence there of the use of brass artefacts before AD43, as a pre-Conquest brass object has been found; a sword found at Isleworth, Middlesex decorated with brass foils (Craddock *et al* 2004). But this is the only know example, and there is no evidence for a pre-Conquest making or melting of brass in Britain (Dungworth 1997) even though there were zinc ores in Britain. Brass used by the Romans in Britain could have been imported from the mines of Stolberg and Aachen in modern day Germany (Craddock 1978; Healy 1978), for example, as there is no evidence of British ores having been exploited by the Romans (Bayley 1998).

2.10.3.2 Cementation

Zinc is a very reactive element and is not found as a native metal in nature. Due to its low boiling point, 907°C, which makes it volatile, zinc would have been very difficult to smelt in antiquity and would be lost in the form of vapour and reoxidised.

Metallic zinc could have been unintentionally produced while smelting other metals, such as lead, from ores containing zinc. To make bronze, metallic tin and copper could be mixed and melted together, an operation that would not work for making brass in antiquity. This is because manufacturing metallic zinc would have required an additional distillation process to condense the zinc vapour produced during smelting, such as that seen in medieval Hindu metallurgy, with later losses of zinc, and overall higher associated costs of time and fuel (Craddock 1978). The use of such a process is not attested in antiquity. Still, zinc metal could have been recovered from the flues of furnaces, such as the droplets found in Laurion and Andeira after smelting lead ores containing zinc, and two later pieces found dated to Roman times, one in Poland and another one in Somerset (Craddock 1998a). However, the production of metallic zinc would have been in extremely low

quantities, very far from the requirements of the brass production seen in the Roman period. Before the invention of the cementation process of brass-making, direct alloying with metallic zinc could have been the only process available to form brass, making it extremely unlikely.

The technical reason behind the choice of cementation is that it does not require the zinc to be present as metal before starting the process. People in antiquity collected the zinc oxide that escaped as a white smoke, an operation which required a specially designed furnace. The zinc oxide was retrieved in the form of a white powder that collected in the furnace flue, which in the presence of small quantities of charcoal (to provide a reducing atmosphere), was added to molten copper in a closed crucible. The resultant metallic zinc vapour would diffuse into the copper forming brass (Craddock *et al* 2004).

Specific details of the brass-making process employed by the Romans are still open to debate, but cementation is generally accepted to be the technique employed (Craddock 1995). Craddock and Eckstein (2003) suggested direct-reduction with zinc oxide reacting with molten copper, as opposed to 'true' cementation, where the metal receiving the diffused zinc vapour would be in solid state at all times. This is important because it would reveal the temperature at which the brass was made; at around 1000°C ± 100 (Bourgarit & Bauchau 2010). It appears that in the literature the term 'cementation' was borrowed from the process of iron carburisation by diffusion in the solid state, and it has been used to describe the diffusion of zinc in copper (regardless of the physical state of the latter) to form brass.

In the case of smithsonite, a zinc carbonate ($ZnCO_3$) ore commonly used in the west (Craddock & Eckstein 2003), calcination reduces the zinc carbonate to an impure zinc oxide. In contrast, sulphide-rich ores commonly used in the Middle East (sphalerite) had to be fully roasted, a process which had as its main objective the removal of the sulphur and forming a relatively pure zinc oxide by sublimation. The zinc oxide was then collected on the walls of the furnace chamber, or on iron rods in the flue above (Barnes 1973).

The second stage is forming brass by cementation, which has an effect on trace elements in the brass produced, depending on whether the zinc oxide employed was obtained by roasting sphalerite or by calcination of smithsonite. In the former case, the zinc is volatilized and purified zinc oxide is obtained, leaving other elements behind as it vaporises. In the case of smithsonite, the impurities (mainly iron, lead and manganese) are retained in the iron oxide and pass to the brass as traces during cementation (Ponting 2006).

Craddock (1995) identified other features regarding individual elements in Roman brass and their relation to the manufacturing process. Traces of tin and zinc contents of 18 to 23% would suggest the alloy to be pure cementation brass. When the tin content is less than 1% it means that it probably originated from the copper used in the cementation process, or as scrap bronze added when remelted. Lead and zinc ores are associated, and cementation brasses always contain at least traces of lead.

Places of production of brass are open to debate. Ponting and Segal (1998) suggest centralization of brass production, given the homogeneity of chemical composition across the empire in the first century AD. This would have required production on a large scale. An imperial monopoly of brass, at least during the first decades of the Empire, was first suggested by Grant in 1946 (Hamilton 1996).

Some very small and slag free mid-first century crucibles were found in civilian contexts at Colchester and Xanten, and were considered by Rehren (1999) and Martinón-Torres and Rehren (2008b) as cementation crucibles. Fragments of these crucibles were examined scientifically, and found to contain high contents of ZnO, but do not have droplets of metal trapped in the slag layer, as in casting crucibles, thus, the suggestion about them having been used as cementation crucibles (Rehren 1999). However, in Lyon, considerably larger crucibles the size of an amphora have been found (Picon *et al* 1995).

At least 270 cementation crucibles for brass making have been found in Lyon, Autun and Alesia. These containers date from the 1st century AD and have a capacity of 30 litres (Desbat *et al* 2000: 184). The cementation function of the crucibles was detected by observing two features on the internal wall. The first one is a change in the coloration of the kaolinitic clay (to blue) due to compositional changes as a result of a very reductive environment. The second indicator of cementation is diffusion of zinc into the wall of the crucibles, which also happens in melting crucibles but in a lesser degree. Desbet *et al* estimated that for a process with an efficiency of 25%, each crucible could have produced 15kg of brass and commented that the presence of identical crucibles in the three different places pointed towards standardisation of brass production. The authors also point out the fact that brass was produced at large scale in locations far from zinc ore sources.

Analysis from copper-alloy objects from 1st century AD Alesia (Rabeisen & Menu 1985), where horse harness equipment was fabricated in workshops amongst other objects, reflects a careful alloying policy. Eleven ingots of irregular shapes and different sizes were analysed and found made of un-alloyed copper, whilst most of the harness fittings analysed were reported as being made of brass. Other types of objects were analysed: rings, figurines and vessels made of bronze,

furniture and jewellery elements (some of which were made of brass) and brass *fibulae* and melting waste. Amongst the copper alloys analysed in Alesia, there are no gunmetals.

Most of the copper ingots are very pure , with all the impurities at trace levels (0.01% - 0.06% arsenic, 0.01%-0.03% nickel, 0.02% - 0.04% antimony, 0.01%-0.05% silver and 0.001% cobalt) for all cases. The presence of copper of this purity together with the brass fittings strongly suggests that cementation brass was being made in the workshop (Rabeisen & Menu 1985: 171). The 20 horse harness fittings analysed have zinc contents ranging from 14% to 23%, and 40% of them have more than 18% zinc. Since these fittings were cast, their zinc contents (even if were made from fresh brass), are expected to have lower zinc contents than if the alloy had been wrought. This is due to an additional re-melt (the primary brass ingot), which would have caused additional zinc loss. Of the 18 remaining brass objects (*fibulae*, decorative elements, and vessels), only 1 contains more than 19% zinc. The trace elements from the analysed brass objects fall in the same order of magnitude that the copper ingots and support the case for brass production in the site.

The fact that Pliny fails to comment upon specific aspects of brass making and the fact that the supply of freshly made brass decreased after the first century AD (Torres-Martinón & Rehren 2008b) could also support the hypothesis of state-controlled and central production of this alloy. There was a decline in zinc content in Roman copper alloys from the third century onwards (Dungworth 1997). In the case of coins this could have been associated with the debasement of silver coins. In the case of military equipment there is a decline in brass use as well, while other copper alloys, mainly cast, got the upper hand. Following the first century AD fresh brass production declined as extant material was diluted forming ternary or quaternary copper alloys containing zinc, now being present in general domestic use (Martinón Torres & Rehren 2008). This could have been due to the reduced availability of brass or caused by a drop in the demand for copper-zinc alloys (which were mechanically worked to shape) as other copper alloys were more suitable for casting (Bayley *et al* 2008b: 49). It seems that brasses were mixed with bronzes to create gunmetals (intentionally or not), which were sometimes also leaded. Leaded gunmetals were widely available by the third century and had some advantages that could explain their success. The tin increases the strength of the alloy, the zinc acts as deoxidant, and the lead improves the casting properties and machinability of the resultant alloy (Craddock 1978).The colour of gunmetals could also have been important for their use: certain compositional ranges for gunmetals, e.g. 4% tin with 6 to 10% zinc, or 10% tin with 3 to 6% zinc, can still give a gold-like hue (Fang & McDonnell 2011).

2.10.4 Ferrous alloys

In general, the technology to cast iron was not available in Europe and Asia Minor until the medieval period, since its melting point, at 1538°C is higher than can be achieved by ancient technology. However, iron ores can be reduced to metal in the solid state as a result of the traditional smelting process to produce an iron bloom that can be refined to iron that can be worked and formed.

Iron ores are generally more abundant than non-ferrous ores, and the furnace technology to smelt them was not very different to that used for copper smelting. In Britain three iron ores are of significance: carbonate, hematite and limonite (Tylecote 1986). Carbonate ores ($FeCO_3$) can be roasted to remove the carbon content as carbon dioxide leaving ferrous (FeO) or hematite (Fe_2O_3), which can be reduced to metallic iron during the smelting process. Limonite ores consists of hydrated iron oxides and hydroxides.

The product of the smelting process is a bloom, composed of metallic iron and slag. Iron could be smelted starting at 800°C but in order to remove most of the slag during the smelt, the temperature had to be raised to around 1150°C (Tylecote 1986), which was still within the technical capabilities in antiquity. Once the bloom was obtained, it was refined by squeezing out the remaining slag by cycles of reheating and hammering.

Transportation of the ore to the smelters was done by the miners, as well as maintenance of the mines. Archaeological evidence has shown that iron blooms were not traded but rather refined directly on smelting. Iron production was widespread across all types of settlement from rural to town environment, and small towns were especially important in it (Schrüfer-Kolb 2004).

In the case of Britain there is evidence of small-scale iron production in the East Midlands and the Forest of Dean before the conquest period, after which production demand greatly increased. The Romans probably took advantage of the potential and incorporated new technologies. It seems that initially major mining regions (such as the Dolaucothi gold mines, the Mendips lead mines, and iron deposits in the Weald) could have been exploited directly by the Roman army after confiscating iron production sites, or they could have demanded iron as a tribute, and automatically absorbed all the established experience and craftsmanship knowledge. At a later stage, for non-ferrous and precious metals, mineral extraction rights were transferred to civilian entrepreneurs (*conductores*) or companies (*societates*), who had to pay royalties, suggesting a free-market economy (Schrüfer-Kolb 2004: 103-122).

Iron is vastly improved in terms of its mechanical properties when combined with small amounts of carbon, which in metallurgy is called an alloy (a metallic solution in solid state in which a metal is mixed with one or more elements). One of several alloys of iron-carbon is steel, which is very sensitive to heat treatment as its internal structure is re-arranged, resulting in high hardness values governed by carbon content. Steels can be hardened after heating above certain temperature (a range between 750 and 1000°C approximately, dependant on carbon content) followed by rapidly cooling (quenching). This improvement in the mechanical properties can also be obtained as a surface treatment. Carbon-steel weapons or tools could be made by carburising and heat treating (e.g. quench hardening) the surface of the object, or by introducing carbon into the alloy by repeated folding and hammer welding. It seems however, that quench hardening was not widely practised by the Romans (see below).

2.11 Metallurgical analysis

Several studies (see below) point to an (close) association of brass with the Roman army. An important case in this respect is that made by brooches, where specific military types (such as the Aucissa and the Hod Hill types) were found to be made of brass and so implying military associations with this particular copper alloy (Craddock & Lambert 1985; Rovira-Llorens 1990; Northover 2000; Bayley & Butcher 2004). Dungworth (1997) however, did not share this view, stating that brass does not particularly feature prominently in military contexts, compared to urban and rural sites, in a survey of Roman metalwork from northern Britain. However in Dungworth's study the proportion of military objects analysed (mainly brass *lorica segmentata* fittings and horse harness equipment, where the proportion of bronze is higher) was significantly smaller than the other categories, potentially affecting the representative value of the data pertaining to military equipment.

2.11.1 Roman metallurgy, scientific studies

Spectrographic analytical techniques are able to quantify trace elements in archaeological objects made of copper alloys, a capability that has been used to study alloying practices, extraction and purification methods in antiquity, and also to try to establish the original ore from which the metal came. However the latter approach has many problems. Craddock (1976) identified three conditions that have to be met for this approach to succeed:

a) The ores in an area need to have a similar composition, which was normally not the case, as ores vary in composition even within short distances.
b) Metallurgical processes not affecting trace element composition from ore to object, which was not generally true, either, as some elements are depleted or enriched during smelting and refining operations, either due to their volatility, or carried off in the slag, introduced by the fluxing agents, or their presence increased by particular affinities between elements.
c) Recycling from different sources was minimal, which was not the case since even the early Bronze Age.

These conditions are rarely met together. By the Roman period, mine shafts could have already been deep enough to introduce important variations in composition, as ore deposits are spatially zoned. However, this situation can be compensated by obtaining a sufficient number of samples to establish a pattern of impurities for the ore in a certain mine (Ixer 1999). Provenance analyses of metals to ore by trace element analysis are rarely useful, having only moderate success when they are coupled with lead-isotope ratio analysis, providing the temporal framework of those analyses are tight, to minimise the effect of recycling. Metal recycling was widely practised in all periods, and this destroys original lead isotope-ratios and affects all trace elements.

Due to the constraints mentioned above, successful studies in archaeometallurgy are generally those of metal characterisation, meaning the use of analytical techniques to describe the chemical contents, structure and properties, rather than trace to source.

A group of three Roman brass ingots in the collections of the German Mining Museum at Bochum was analysed by atomic absorption spectrometry down to trace elements (Weisgerber 2007). It is thought that the ingots came from a shipwreck east of Corsica, but do not show any stamp. The chemical composition, which showed the ingots to be primary brass, show distinctive trace element levels for the three ingots: silver (0.045,0.065,0.090%), nickel (0.25, 0.038, 0.05%), arsenic (0.08,0.1,0.4%) and antimony (0.05, 0.11, 0.8%). This is important because some of these elements, like silver and nickel are less affected by metallurgical operations such as re-melting. In this way, objects could be associated with the workshops that produced these ingots.

Craddock (1976) mentions large scale metalwork analysis of Roman artefacts in addition to his own work, mainly obtaining chemical composition and major element constituents. Boesterd and Hoekstra (1966) analysed 300 Roman vessels from the museum at Nijmegen; Picon, Boucher and Condamin (1966, 1967 & 1969) analysed 300 Gallo-Roman bronzes from French museums; Smythe (1938), analyzed artefacts from Roman Britain; and Caley (1964), who specialized in coins.

Zinc, tin and lead contents in the bulk of the metal are important in Roman brasses used to identify recycling patterns and technological choices. Craddock (1978) identified three groups by zinc content when analysing Roman brass objects. The first group contained less than 4% Zn, where brass presence can be considered unintentional. The second group contains 22 to 28% Zn and represents freshly made brass. The third group is constituted by copper alloys resulting from mixing primary brass with scrap bronze, resulting in contents between 4 and 20% zinc.

Once a clear idea of the constituents of Roman alloys and their general compositional range had been obtained, specific types of objects or alloys and their distribution association with specific groups (e.g. brass and the military) were studied. In addition, more emphasis was placed on trace element analysis for characterization and possible grouping.

Beck *et al* (1985) showed, with the aid of lead isotope studies, that there were regional "schools" characterized by typical alloy recipes, with workshop secrets being preserved. Metal was recycled, as mean zinc contents of 10% reveal, but within the same region. This was supported by a study at Alesia (Rabeisen & Menu 1985), showing that brass was worked in specialized workshops, as only brass was found in two out of five workshops. The same situation appears to be present at Titelberg, in Belgic Gaul (Hamilton 1996), whence 120 copper-alloy objects were analysed. A wide range of elements, including traces were measured (copper, tin, lead, zinc, iron, arsenic, silver, antimony, sulphur, nickel, cobalt, and chlorine) by proton-induced x-ray-emission spectrometry (PIXE) together with some metallographic analysis of *fibulae*, pins, and other fittings.

Craddock and Lambert (1985) stated that 50% of Roman decorative metalwork and nearly 100% of the military decorative metalwork of the first century AD contained zinc, and suggested that the main sources of brass in the provinces were Roman coins and Roman military fittings.

When analysing objects from over an extended period of time (1500 years up to the 6th century AD) from South Cadbury, Northover (2000) showed that metallurgical analysis can be useful to identify alloys and impurity patterns to associate objects with specific groups and periods of time. This type of analysis also helps to understand the metal economy in different periods, and to shed light on production techniques. Northover included Bronze Age, Iron Age and Roman metalwork. Thirteen elements from these objects were analyzed by electron probe microanalysis (EPMA) with wavelength dispersive spectrometry. Even if the data cannot be used together with those from atomic absorption spectrometry for trace element analysis, since WDS is not as sensitive as AAS, they can still be compared together with the elements used for alloy-type classification of Roman alloys: tin, zinc, and lead. Most of the objects analysed were brooches, of which 67.7% were bronze (mostly unleaded), 19.8% brass, and 12.5% gunmetal. Northover contrasted this information with

data from brooches from Camerton and Colchester (where 46% and 90% respectively of the brooches found are brasses), concluding that certain brooch types associated with the military, such as the Aucissa and Hod Hill types, tended to be made of brass. This observation is in agreement with a previous large survey of brooches in Britain by Bayley (1998) and also valid for other parts of the Empire, like Spain, where Rovira-Llorens (1990) found that brass predominated in military brooches.

Dungworth (1997) analysed a large number of Iron Age and Roman copper-alloy objects from northern Britain, comprising diverse categories (e.g. personal, household, transport, and military items). Nine elements (copper, zinc, tin, lead, iron, nickel, arsenic, manganese and cobalt) were quantified, but the overall conclusions are associated mainly with major and minor elements (copper, zinc, tin, and lead). Again, it is reported that the use of brass is higher for transport and military items. It was also found that the Roman alloys in the study generally contained lower quantities of trace elements, except for iron, than Iron Age alloys.

2.11.2 Roman military equipment analysis

Bishop (1985b) has noted the lack of any comprehensive metallurgical analysis in Roman military equipment of any period. Scientific analysis of Roman military equipment has been relatively scarce and has tended to comprise microstructural analysis of ferrous materials, mainly weapons, or chemical analysis (qualitative or quantitative) of objects from specific sites as part of excavation reports or small finds publications, such as those from Haltern (Riederer 2002) or Camerton (Cowell 1990).

2.11.2.1 Ferrous alloys

In the case of ferrous alloys, some occasional examples of research assessing physical properties of military equipment have appeared in the past and show diversity in the internal structure revealing variety in metallurgical aspects of the manufacturing processes, such as heat treatment and cooling conditions.

A possible Roman sword from Waltham Abbey with very low carbon content (ranging from 0.25%C to pure iron) did not show any quenching or surface carburisation (Lang & Williams 1975). Williams (1977) analysed a *gladius* from the Rheinisches Landesmuseum in Bonn and a *lorica segmentata* fragment from Ristissen. His study revealed an internal structure of non-hardened mid-carbon steel in both items which were probably air-cooled. A section of the sword was examined

metallographically, revealing a ferrite-pearlite structure (microstructural equilibrium phases characteristic of mid-carbon steels, this is 0.3% to 0.7% carbon content by weight) gradually increasing in carbon from the centre towards the surface. The armour plate is made of also heterogeneous steel with carbon content varying from 0.2 to 0.7%.

Tylecote and Gilmour (1986) published a metallographic study of diverse edged tools and weapons, amongst which we can consider an arrowhead and a dagger from Brancaster, a spearhead from The Lunt, and a *spatha* from Whittlesey, Cambridgeshire. The dagger, iron arrowhead and spearhead showed a ferritic structure with very low carbon content and low hardness values (around 120HV). The microstructure of the sword consisted of relatively uniform ferrite and pearlite. The sword was probably build from three parts, each with different hardness values (from 157 to 193HV and is composed of low carbon steel, thus having good toughness. Again no heat treatment was observed for this sword.

Lang (1988) correlated a shift in technology with changes in the organisation of the Roman army more specifically that the transition from 'Mainz' to 'Pompeii' type of *gladius* was related with change in metallurgical techniques. Three pre-AD50 swords were found having been quenched and with martensitic edges making them hard (martensite is an acicular shaped microstructural phase that forms when iron-carbon alloys are rapidly cooled from a minimum critical temperature; in this case from around 800°C). In contrast, the other three post AD50 swords, showed lower carbon content and no hardened edges. In the same work, Lang reports a *gladius* from Windisch (second half of the first century to early second century AD) with a carbon enriched surface, and a *spatha* from Augst, dating from the mid-second century to the third quarter of the third century AD, which was quenched and tempered. However, Lang is cautious in saying that manufacturing processes could have been related to status as well, and some swords that entered the archaeological record, specifically those ritually deposited in rivers, are not necessarily representative.

When trying to understand why Romans used iron alloys in their armour, Fulford *et al* (2005) performed a thorough chemical (qualitative non-dispersive XRF) and metallographic analysis, as well as measuring hardness and studying the inclusions present, of some armour samples from different sites: Haltonchester, Newstead and Carlisle. By examining the structure, the authors reported that no quenching and tempering (moderate heating after quenching to relieve the material from the thermal stresses caused by rapid cooling) was used in the armour production, and that Romans were able to do carburisation treatments even if it was not done consistently. Technological choices were explained by costs and functionality. For instance, it was argued that ferrous equipment was cheaper to produce and generally better in mechanical performance than its non-ferrous counterpart. The

authors complained about the studied of materials in military equipment being biased towards the analysis of weapons.

2.11.2.2 Copper alloys

Traditionally, scientific analysis of copper-alloy Roman military equipment has been done to obtain the general alloy-type distribution of an assemblage, or to associate a particular alloy range of composition to a type of object or to determine membership of objects within a group, such as a hoard or a workshop, by the presence or absence of specific trace elements. An alloy-type study could require no more than a surface analysis technique, providing access to an internal surface of an object is available, or if a surface is representative of the whole object. Trace element analysis needs more sensitive techniques, such as inductively coupled plasma- mass spectrometry (ICP-MS) or atomic absorption spectrometry (AAS, see Chapter 3). Occasionally, the composition of decorative features, such as plating or enamel is analysed. Some of the relevant studies are mentioned below.

In 1989, Bishop analysed copper-alloy Roman military equipment from Longthorpe, including some down to trace elements: rivets, strap and *lorica segmentata* and *hamata* fittings. The technique used was atomic absorption spectrometry (AAS) and the elements measured were copper, zinc, tin, lead, antimony, iron, nickel, chromium, silver, cobalt, and manganese. However, the results are expressed in terms of minor or major elements levels of resolution (order of magnitude of unity). Bishop concluded that even if recycling was practised, different types of brass could have been kept separately to be used for different types of objects, since particular recipes were probably used for specific purposes, this being consistent with horse trappings from Fremington Hagg and Xanten.

In the case of Xanten, the pattern of presence of certain trace elements (also obtained by AAS) led the authors to conclude that the trappings were made in the same workshop (Craddock & Lambert 1985). With regard to the Fremington Hagg hoard, Craddock *et al* (1973) compared the chemical composition (AAS was again used) of certain horse-harness fittings in the Yorkshire Museum to others in the British Museum. The objective was to establish if they all belonged to the hoard. The conclusions were positive; after comparing the composition of these with unrelated fittings from Xanten and reporting low variability of the quantities of major and minor elements in the objects from the British sites it was concluded that the British Museum harness fittings were indeed part of the Fremington Hagg hoard.

Dungworth (1997) also included military objects from the early Empire and from the 2nd and 3rd centuries in his analysis of Roman alloys (mentioned above), such as *lorica segmentata* fittings, *lorica squamata* scales, and cavalry pendants. He noted the decrease of zinc content in brass corresponding with an increase of tin, with gunmetals and bronzes becoming dominant after the 2nd century, following the tendency of Roman copper alloys. In general, brass accounts for 37% of the alloys from the 1st century AD analysed in the study, while leaded bronze and leaded gunmetal together represent 27%. For the 4th century alloys brass amounts to just 4%, while 64% are leaded bronzes and leaded gunmetals. For Dungworth, this decrease occurred due to a deliberate alloying policy, as opposed to simply the recycling of scrap coins. Specific alloys, obtained by mixing weighed quantities of brass and leaded bronzes, could have been chosen for their properties; colour, sound and texture, all of which would have carried social meanings.

Ponting and Segal (1998) and Ponting (2002) characterised Roman military equipment from Masada and Gamla integrating alloy type, trace element analysis (by ICP-AES) and fabrication techniques to argue for the association between military and brass production in Palestine. The trace element contents showed that the brass from which the military objects analysed were made, was produced using smithsonite ores and therefore imported from European workshops.

Other examples of using trace element techniques include:

- Jackson and Craddock (1995), analysed the Ribchester hoard, giving explanations for the degree of presence of certain elements (major and minor) in Roman brass;
- Cowell (1990) in his scientific report for mid-first century AD Camerton (Somerset), analysed diverse objects down to trace element levels, which include Roman and Iron Age military equipment;
- Riederer (2002) analysed 56 military equipment objects from another of the Roman fortresses in Germania Inferior, Haltern.
- Šmit *et al* (2005) performed chemical analysis on sword and dagger scabbards and fittings from the river Ljubljanica, Slovenia by particle-induced-x-ray-emission spectrometry (PIXE), a surface microanalysis technique used in this case for obtaining an estimate of the bulk composition of major and minor elements in iron and copper alloys (copper, zinc, tin and lead). Additionally, special attention was given to the plating composition (tinning, gilding, pewter) and enamel on the objects. The authors discovered tinned brass scabbard fittings and hand-guard plates, and pewter (a tin-lead alloy) used as plating.
- A group of other enamelled brass military decorative objects from a Roman villa at Wange (central Belgium) was subjected to metallographic analysis by optical and scanning electron

microscopy (Lodewijckx *et al* 1996). The technique used by the Romans to directly enamel copper alloys is not fully understood yet. The authors suggested a possible application method that the Romans could have used so that adequate levels of adherence between enamel and the copper-alloy substrate could be obtained.

2.12 Conclusion

The organisation of troops in the years following the invasion of Britain and the positioning of military units in forts and fortress is largely speculative (see Chapter 4). Legions could have been either at full-force in a fortress, split across two or three bases at a time, garrisoned with detachments of other legions, or occupying a fortress for only a brief period of time. The previous history of the invading legions, and with it the possible supply sources of their equipment, is not clear at all. Metallurgical fingerprints for a representative number of objects from a specific period of time could contribute significantly to our knowledge of the garrisoning of different sites and movement of troops in the first and second centuries AD in Britain. Metallurgical links between troops arriving from Germany for the conquest can also be explored. As seen in this chapter, scientific studies are a relatively recent phenomenon in Roman military equipment studies and have generally been constrained to individual sites, or to employ either chemical composition or microstructural (rarely) analysis. The research described here employs both strategies on material from several sites.

Variables that can influence the chemical composition of copper-alloy artefacts are the chemical composition of the original ores smelted, smelting and refining, recycling, and addition of other elements (both intentional and unintentional). Major elements mixed with copper, such as tin, zinc, and lead can be related to metallurgical traditions. They can reflect intentional technological choices that have an impact on mechanical properties and visual appearance. Specific trace elements associated with copper (nickel, cobalt, silver, antimony, arsenic), are less likely to be affected by metallurgical operations and can therefore be used to characterise the alloy. Sensitive chemical analysis is needed, however, so that elements present at trace levels (<0.1%) can be quantified (see Chapter 3).

As explained above, attempts to establish a link between the chemical composition of a copper-alloy object and the ore from which it was made and are generally futile exercises. Extensive recycling destroys patterns that could be associated with ores had the object been made with fresh metal from a specific ore. However, regionally closed systems of recycling pools supplying military

units could be characterised chemically and microstructurally to help identify military units, metallurgical traditions by type of object, or reflect a technological choice in decoration and personal display.

The visual aspect of the equipment seems to have been of prime importance, and in the case of metals it is directly dependant on technological processes and choices. Copper alloys can resemble gold in lustre and colour when specific ranges of tin and zinc concentrations are used (Fang & McDonnell 2011). The choice of the compositional range of zinc for brasses and certain ranges of gunmetals, used for a great variety of military fittings in the first two centuries AD could have been the product of technological choices aiming for a specific appearance. Plating (tinning and silvering) created contrast and offered the possibility of displaying patterns, such as the alternate tinned and non-plated brass *lorica squamata* scales found at Ham Hill, or those reported from Carlisle (Howard Davis 2009).

Additionally, microstructural analysis can reveal the manufacturing method of the object from the raw metal, inform on mechanical properties and performance, and can also identify the method used to apply plating. Characterising copper alloys, chemically and microstructurally is likely to require a tight temporal frame, so that these variables do not change to the point that they become unrecognisable. Furthermore, the sample size needs to be statistically significant. In the next chapter, the techniques chosen for the analysis of the samples in this thesis and the methodology of analysis employed are presented and discussed.

Chapter 3: Methodology

In this chapter, the overall methodology of the analysis of the material discussed in this thesis is explained, followed by a definition of Roman copper-alloy types, with their major, minor, and trace elements. An explanation of the techniques normally available for bulk chemical analysis is given and the choice of the ones used here is explained. This is followed by the criteria of selection for the assemblages analysed for this project and the explanation of the analytical and statistical techniques employed, summarising their fundamental principles, limitations, sampling and analysis procedures for each case.

3.1: The integration of analytical chemistry and metallographic techniques.

The strategy of analysis that was followed in this project includes two independent analyses of the objects as a first stage. The first one was a bulk chemical composition by atomic absorption spectrometry (AAS) of the objects sampled. AAS is capable of quantifying the whole compositional range of metallic chemical constituents in the bulk of the object (see Section 3.7.1), which allows for complete chemical characterisation. The second type of analysis was a physical evaluation of the internal microstructure of the objects (metallography), which provided information on fabrication techniques.

As was set out in the introductory chapter (Chapter 1) this project aims to identify the metallurgical fingerprints of specific military units and/or workshops. As such, quantifying the chemical composition (major, minor and trace levels for a suite or relevant elements) for the totality of the sampled objects was the top priority. However, since for a complete characterisation information about fabrication techniques and mechanical properties is needed, a significant proportion of objects from each assemblage (1/3 of the total amount of objects) were analysed metallographically.

Once compositional information was obtained, uni- and multivariate statistical analyses were performed on the data to identify ranges of composition, distribution and correlation of the different elements. This was done first on a site-by-site basis, and then by combining different sites, and was followed by comparing metallography data between sites and between artefact types.

3.2: Roman copper alloys

Traditionally, metals in archaeology are divided into two broad groups, ferrous and non-ferrous; the latter meaning that they have an element other than iron as the main constituent. The study here involves the analysis of non-ferrous metals, specifically copper alloys.

An alloy is a substance that has metallic properties and which is composed of two or more chemical elements, of which at least one is an elemental metal (Avner 1974: 668). In old excavation reports, especially those published in the first half of the 20th century, copper-alloy small finds are generally, and in many cases wrongly, labelled as 'bronzes'.

Terminology varies between archaeology and materials science or metallurgy, and archaeological material differs substantially from modern alloys. However, definitions are qualitatively similar for both metallurgy and archaeology. Bronze is a copper alloy containing mainly tin, while brass has copper and zinc as its main constituents. Gunmetals are mostly copper with important additions of tin and zinc. These three groups of alloys can also contain lead as a major element. It is normally considered that a presence of 2% or above of alloy components is indicative of deliberate addition of the element in question (Rabeisen & Menu 1985). In the case of Roman alloys, these elements are lead, tin and zinc. Elements present at trace levels are considered apart from copper, lead, tin, and zinc because it is unlikely that they were added deliberately (Hamilton 1996).

3.2.1 Major elements

In the case of Romano-British metalwork, brasses generally contain 10-25 wt% zinc, bronzes 5-15% tin, and gunmetals several percentages of both tin and zinc. Leaded copper alloys have over 4% lead, but most contain over 10% and some more than 20% (Bayley 1998). Alloys, defined by major elements, can sometimes be used to determine cultural groups and trace groups of people (Hamilton 1996).

For Roman military equipment, brasses and bronzes are considered as copper alloys containing 5 to 25% zinc and more than 2% tin, respectively. If the alloy contains more than 5% zinc and 2% tin together, it is then called gunmetal. As implied above, the metal is considered to be leaded (implying deliberate addition of lead) if any of these three types of alloys contains more than 2% lead (see Figure 3.1).

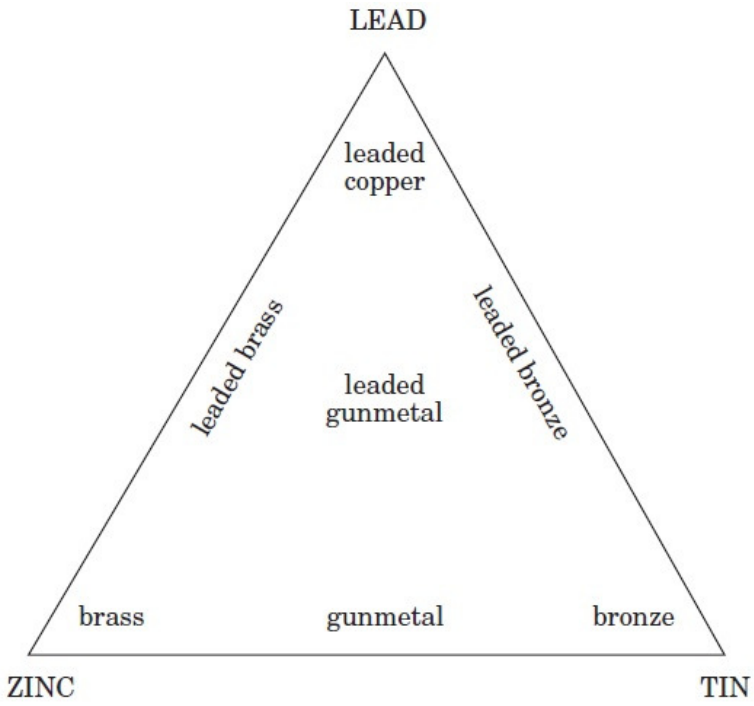


Figure 3.1 Ternary diagram showing Roman copper-based alloys as defined by their zinc, tin and lead content (from Bayley 1998: 8).

3.2.2 Minor and traces

Copper, tin, zinc and lead are major constituents (more than 1%) quantified to define alloy type. However, the resolution required for this work is of a much higher order, involving bulk quantitative analysis of minor (from 0.1 to 1%) and trace elements (less than 0.1%, down to a few ppm; Christian 2004: 15).

Analytical techniques have been used in some studies to establish copper ore sources. The range of variation of trace level impurities can provide some clues to the homogeneity of the ore sources (Hamilton 1996). However, the elements measured have to be chalcophilic (with a strong affinity for copper), so that they are not lost during the smelting processes. But the results will be different if the ore in question is a carbonate or a sulphide. Molybdenum (Mo), sulphur (S) and phosphorus (P) could be of importance in such cases. However, if the data obtained from metal objects are to be used for establishing sources at a workshop level, a suite of metallic elements can be used (Gilmore & Ottaway 1980; Pernicka 1987; Hauptman 2007): copper (Cu), tin (Sn), lead (Pb), arsenic (As), antimony (Sb), silver (Ag), nickel (Ni), bismuth (Bi), gold (Au), zinc (Zn), cobalt (Co) and iron (Fe).

The smelting process affects trace elements present in ores in different ways, depending on the specific element and furnace conditions (temperature, type and quantity of flux, oxidizing or reducing atmosphere, and time). A proportion of each of the elements present in the ore passes into

the metal and another is carried off by the slag produced in the presence of the flux. This phenomenon is called partitioning or fractionation and can be represented for each element as a mathematical coefficient (Hauptman 2007):

$$D_{Cu/S} = (\%M \text{ in copper}) / (\%M \text{ in slag})$$

where, %M is the percentage of a trace element, and D is the partition coefficient

If D<1, the element in question will concentrate in the slag, whereas if D>1, the element will concentrate in the metal (enrichment). For the Roman period the partition coefficient has positive values in most cases for arsenic, nickel, cobalt, and lead, and in many cases for zinc (Hauptmann 2007). The order of enrichment in metal, (partition coefficient values in descending order) is As>Ni>Pb>Co>Zn>Fe.

The different behaviour of trace elements can be diagnostic of technological processes associated with cultural groups. For example, arsenic and nickel seem to be stable under different oxygen pressures or firing conditions. Some elements like nickel and cobalt have very similar partitioning coefficients in Roman times, in contrast with previous periods, where nickel is relatively enriched in comparison to cobalt. This is explained by the fact that, under poor reducing conditions, cobalt is transferred more readily than nickel into the slag. This is unlikely to be the case under the strongly reducing conditions generally accepted at having been the case with Roman smelting (Hauptman 2007). Other elements like arsenic are more time and temperature dependent in their partitioning during smelting (Pollard *et al* 1990). Silver is another useful element whose concentration in copper does not change significantly during the smelting process (Tylecote *et al* 1977).

Pernicka (1999) mentioned nickel and silver, and cobalt, arsenic, and antimony amongst the elements useful for provenance and/or technology association, respectively. For instance, a higher proportion of arsenic and antimony would be obtained by direct reduction smelting, whereas smelting after roasting would drastically affect their levels in the obtained metal (Tylecote *et al* 1977).

Subsequent processes such as refining, where re-melting is involved can also affect the quantities of the elements involved. For example, re-melting would cause the loss of some nickel (Pernicka 1999), or zinc, of which about 10% is lost in every re-melt (Bayley 1998: 21).

3.3 The relative merits of analytical techniques commonly used in archaeometallurgy (NAA,ICP-MS, MC-ICP-MS, ICP-AES and AAS)

There are diverse analytical techniques that can be used to measure bulk chemical composition capable of measuring trace elements with concentrations in the range of parts per million (ppm) or less, such as neutron activation analysis (NAA), inductively coupled plasma mass spectrometry (ICP-MS) and atomic emission spectrometry (ICP-AES), or atomic absorption spectrometry (AAS).

NAA is a technique with a long history of use in archaeology, especially in provenance studies of pottery, copper alloys, lead and glass (Kuleff & Djingova 2007). This technique works by placing the sample in a dense flux of neutrons. Some atoms of the sample capture the incoming neutrons, becoming radioactive unstable isotopes, whose decay is measured, giving information about specific chemical elements and their concentration (Bowman 1991: 182). A variant of this technique is fast neutron activation analysis, which uses higher energy neutrons than NAA. This technique is able to accurately analyse trace elements in the sample in concentrations less than 10 ppm (Pollard *et al* 2007: 130) and requires a sample size of normally 50mg (Bowman 1991: 182), which is much larger than that required for atomic absorption spectrometry. Two clear disadvantages of this technique are its extremely low sensitivity for lead detection (Konya and Nagi 2012: 291), and thus unsuitable for the analysis of Roman copper alloys, and that a nuclear reactor is required to provide the neutrons. NAA is mainly used for the quantitative analysis of trace elements if a high level of accuracy is required, and Tite (1972: 277) reports that NAA is sometimes not very accurate when trying to measure major elements. This technique is mainly used in ceramics analysis, since the sample does not require dissolution and accepts solid samples (Speakman & Glascock 2007).

Mass spectrometry (MS) aims to identify an elemental constituent by means of its atomic mass, by generating ions (atoms where the number of electrons is different to the number of protons, and thus having positive or negative charge) from the sample. These ions are then separated by their mass-to-charge ratio (m/z) and their abundance measured. Ionization can be produced by several means, one of which is via an inductively-coupled plasma (Gross 2011: 6-7). ICP-MS has higher speed and sensitivity compared to atomic absorption spectrometry, having minimum limits of detection in solution of the order of parts per trillion (ppt) for some elements (Pollard *et al* 2007: 60). ICP-MS offers higher sensitivity and lower limits of detection compared to atomic absorption spectrometry. However, it suffers from matrix interference effects, does not cope well with high concentrations of analytes and is very costly to run.

Whilst ICP-MS is employed for elemental analysis, multicollector ICP-MS (MC-ICP-MS) uses several detectors capable of measuring different masses. This accounts for instabilities caused by the use of a plasma ion source. The result is the capability of measuring ratios of isotopes (atoms with the same number of protons but different number of neutrons) of elements, such as lead. MC-ICP-MS has become the dominant chemical analysis technique for archaeological lead isotope provenance and geochemical fingerprinting studies (Baker *et al* 2006; Ponting 2003), taking over thermal ionization mass spectrometry (TIMS). ICP AES uses ionized matter as an excitation source, as does ICP-MS. A sample in liquid form is aspirated by a pump and injected into an argon stream, which serves as a carrier into a torch. Plasma is then formed and the constituent compounds are dissociated and reach an excited state. Excitation in the atoms produces characteristic emission lines for each element in the visible and ultraviolet range of wavelengths and is then received by a detector, which sequentially measures the emission intensity for each element analysed. ICP-AES offers higher sensitivity than AAS (due to the higher temperatures achieved, that ensure a more complete atomization and less interference between spectra), but lower than ICP-MS (Pollard *et al* 2007: 60).

AAS (described in Section 3.7) was chosen for this project due to its ready availability, its low operation and maintenance costs, and the fact that it excels in the analysis of low concentrations of metals, which are represented in this project by trace elements in copper alloys. In addition, the nature of the samples required by AAS allows them to be obtained without having to remove the objects from their collections at any stage.

3.4: The selection of geographical area of study and temporal framework

The first part of this project involved gathering as much information as possible about the existing finds of Imperial Roman military equipment from across the empire and from several periods of time. The main purpose of this database was to identify a set of assemblages having a statistically significant sample of objects (over 20) of the same type and in suitable condition for metallurgical analysis. However, it could also be useful to identify certain concentrations of specific types of military equipment in determined geographical zones.

In many cases military equipment is difficult to define. It can be described not only as those items that a soldier brought to battle, but also as those objects that were used by military personnel in daily-life situations. For Dufrasnes (2008) many of the reported 'military' harness fittings in Germany and Britain frontier systems were not necessarily used by soldiers. He argues that they were found in civilian areas. Feugère (2002) notes that it is sometimes very difficult to distinguish between military equipment and some other applications, especially in civil contexts like some *vici*.

Some objects are of ambiguous function, like decorative studs in belts that could easily belong to furniture or to vehicles, or buckles that could be part of a horse harness or a soldier's baldric. Others are of unclear military association, such as button-and-loop fasteners, of which a third come from native rather than military sites near Hadrian's Wall (Allason-Jones 1989).

For simplicity and analysis purposes, those types of equipment included in Bishop and Coulston (1993; 2006) will mainly be followed in this study, these are items that are thought to have been worn when troops were in action. Objects such as brooches, hobnails, tools or metal vessels are left out of the project. Only metallic military equipment was considered, of which almost all the metal finds were copper alloys or iron. Lead, for instance, was used for certain items (such as artillery shots) or in parts of the *plumbatae*, probably to turn them into weighted spears (Bennett 1991). Due to the general lack of chemical analysis in most of the sources consulted, bronze, brass and gunmetal finds were referred to as 'copper alloy' objects when forming the database.

It appears that many items of military equipment, mainly those of copper alloys, would have been originally tinned, silvered or even gilded. It is important to take into account that plating was sometimes identified and reported on publications, but it is possible that on many occasions this fact was overlooked, destroyed by cleaning with aggressive media or simply not identified because corrosion processes often obscure any remaining plating.

The objects in the database are grouped into three main categories, each with its own set of sub-categories, derived from Bishop and Coulston (2006):

- 'Weapons' (including weapon parts and fittings): *pila* (points, heads and shanks); spears (lances, darts, spearheads, blades, sockets and spear-butts); swords (blades, hilts, pommels, slides, guards scabbards, chapes and mounts); daggers (with hilts, scabbards, chapes and mounts), archery equipment and slings (arrowheads, sling shots and bow fittings), artillery (bolt-heads, catapult frames and washers);
- 'Armour': body armour (*lorica hamata*, *lorica segmentata, lorica squamata,* as well as their fittings and parts), helmets (including, cheek pieces, ornamental bosses and other fittings), shields (bosses, grip bars, lining, mounts); and
- 'Other Equipment': belts (with hinges, plates, mounts, fasteners, pendants), aprons (mounts, strap terminals), baldrics (mounts and fittings), obstacles (caltrops), pendants and appliqués, and equine equipment (*phalerae*, pendants, harness fittings, bits).

A second database was created composed of a random sample of 550 bibliographical references from publications ranging from the late 19th to the early 21st centuries to identify those

countries that have dominated Roman military equipment research, and thus in that way to identify biases that could help to explain the artefact database. Analysing the publications by country and by year not only gives a historiographical insight, but also helps to identify other biases in the overall analysis of the database that could be introduced by the presence of single sites with hundreds of finds, or those sites with incomplete or minimal information in the database, that actually should have a greater number of artefacts that could be considered in the sample.

The sample for the database of references was taken from publications (in different European languages) that report on Roman military equipment from all periods of time and all places. About 25% of the sources were later used to feed the military-equipment database. This sample shows distributions that are heterogeneous in terms of the countries that contributed to it or in terms of the date when these publications appeared. The distribution by country (Fig. 3.1) is heavily tilted towards British and German publications. In fact, these two countries account for 75% of the number of publications in the sample, with the UK alone contributing with 45%. Romania, France and the Netherlands together form 13%, of the publications.

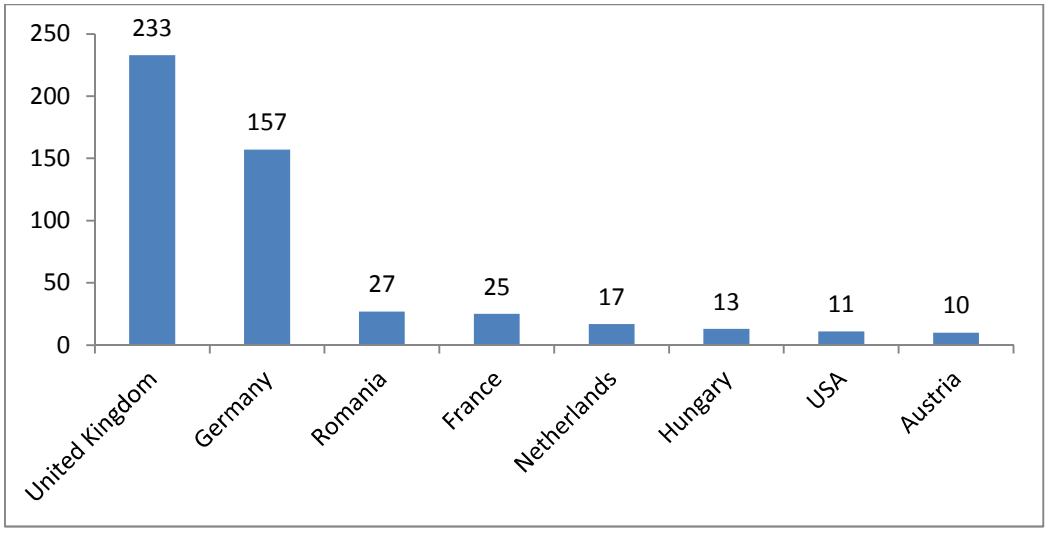


Figure 3.2 Number of publications by country.

Years of publication of the sample go from 1863 to 2010 (Fig. 3.3). Sources seem scarce from the 1860s to the beginning of the 20th century. Here the number of publications slightly increases, and the distribution appears to remain stable until the 1950s. From the 1950s to the 1970s the increase is now more pronounced, and reaches a peak in the 1990s.

If the contributions from UK and Germany, are plotted in a single graph (Fig. 3.4) similar behaviour is observed, besides the absolute number being almost always lower for Germany. There is a slight decrease in the growth rate of German publications between the 1980s and 1990s.

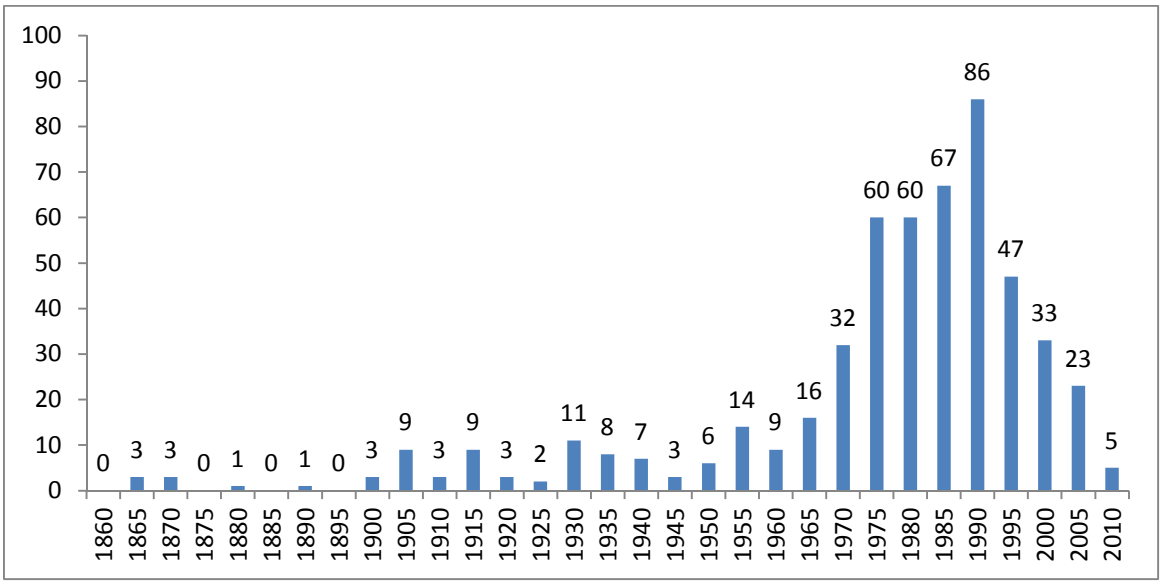


Figure 3.3 Numbers of publications in the sample by year.

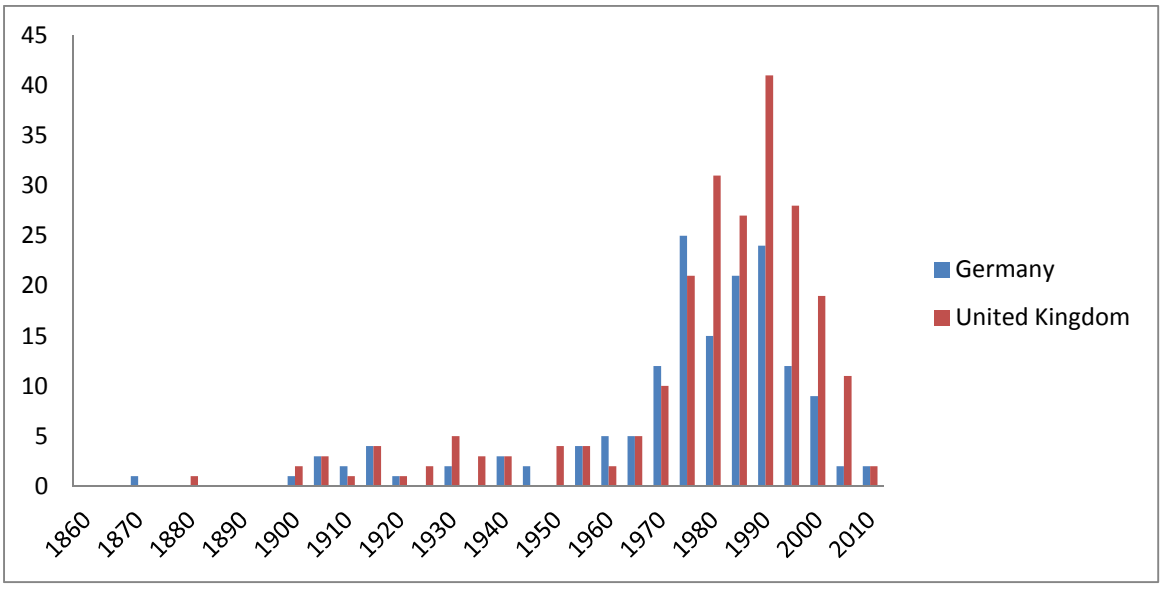


Figure 3.4 Numbers of publications by year for the two main contributors to the References sample.

The fact that both Germany and Britain show a similar tendency over time (Fig. 1.3) gives a broad qualitative reliability to the reference sample, in terms of reflecting how research has taken place in the 20th century. However it does not necessarily mean this tendency reflects the real situation about the distribution of the equipment, since more excavations and more research can obviously lead to further research and an abundance of reports.

3.5: The selection of assemblages

3.5.1 Main types of finds in Britain

Some of the most abundant types of military equipment in Britain coincide with those Bishop (1987) identified as useful change indicators, namely cavalry pendants, belt-plates and body armour fittings (especially *lorica segmentata* fittings). Scabbard fittings and spearheads have the highest numbers for offensive weaponry.

Figures 3.5 to 3.9 show the main types of finds in Britain found in the database, and the most relevant (according to the database) from the first century are:

- Figure 3.5 shows the sites in the database with the highest number of scabbard fittings. Part of this type of find at Colchester is from the mid-first century, as are those from Chichester, Waddon Hill, London and Longthorpe.
- For spearheads (Fig. 3.6) Hod Hill, Cadbury Castle and Kingsholm.
- For body armour (Fig. 3.7) Newstead (late first century, appearing with many finds because of *lorica hamata* scales), Ham Hill (large number of scales as well), Colchester (from the AD60s), Chichester, Richborough, Longthorpe and Cadbury Castle.
- For belt-fittings (Fig. 3.8) Colchester, Cirencester, Kingsholm, Wroxeter and Chichester.
- For equine equipment (Fig. 3.9) Fremington Hagg (cavalry equipment hoard), Colchester, Newstead, and Cirencester, The Lunt, and Hod Hill (Bishop 1988). This can be seen in Table 3.1.

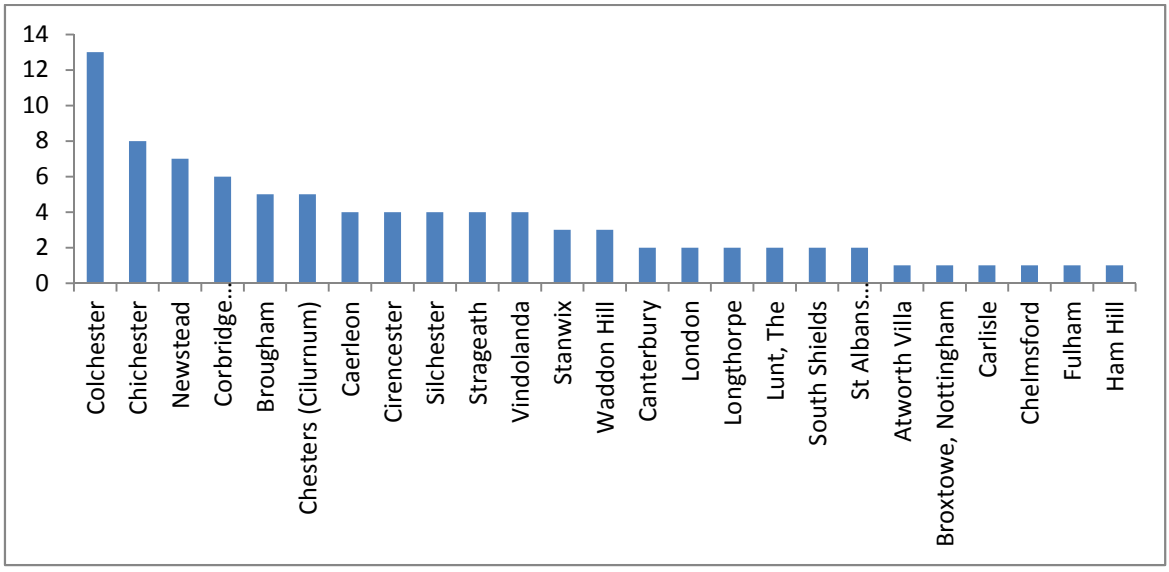


Figure 3.5 Scabbard fittings in Britain (dated finds).

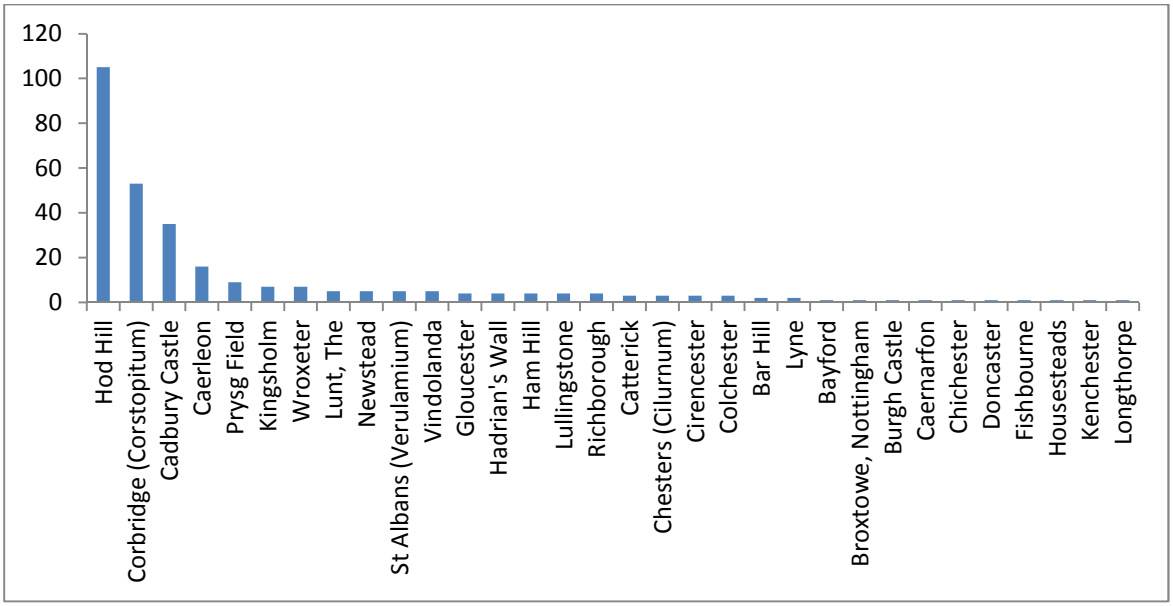


Figure 3.6 Spearheads in Britain (dated finds).

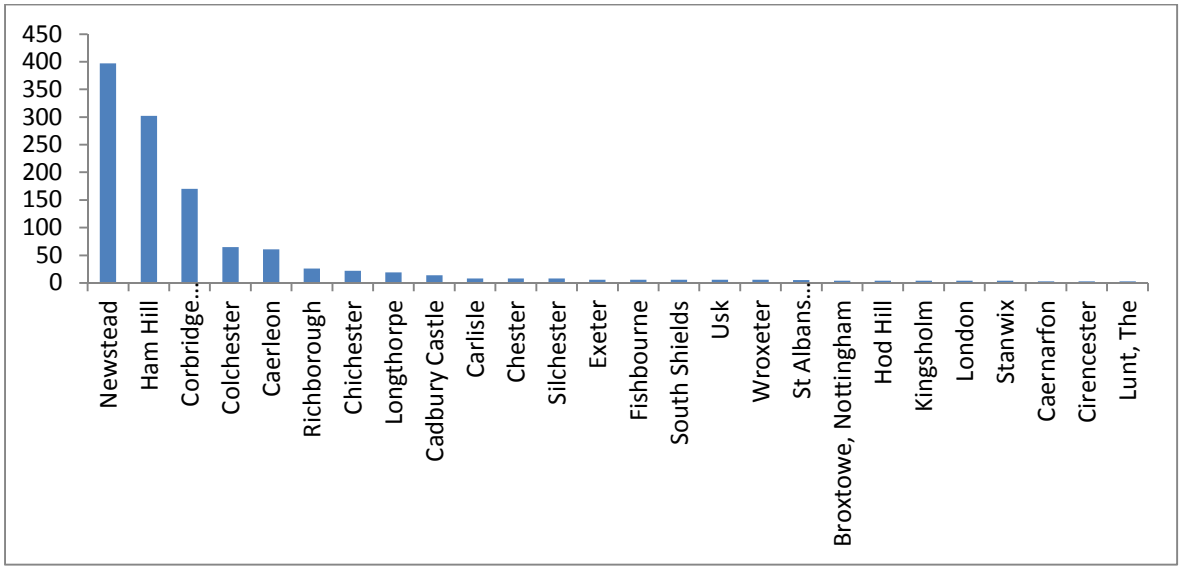


Figure 3.7 Body armour equipment in Britain (Dated).

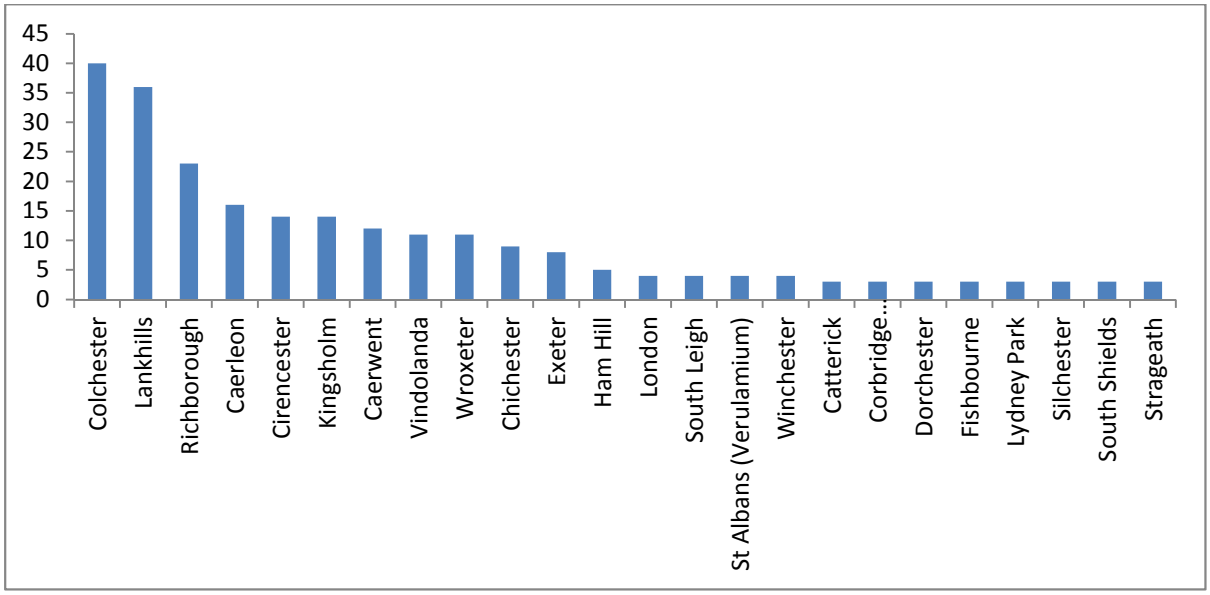


Figure 3.8 Belt fittings in Britain (Dated).

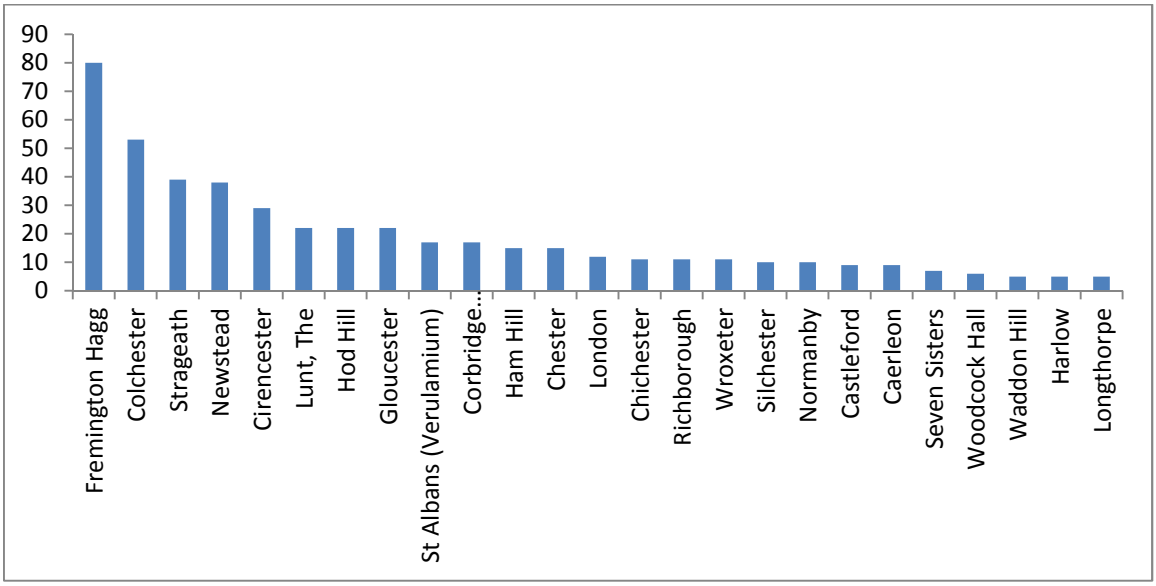


Figure 3.9 Equine equipment in Britain (Dated finds).

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Body Armour	Newstead	Ham Hill	Colchester	Chichester	Richborough	Longthorpe	Cadbury Castle
Equine Equipment	Fremington Hagg	Colchester	Newstead	Cirencester	The Lunt	Hod Hill	
Belt Fittings	Colchester	Cirencester	Kingsholm	Wroxeter	Chichester		
Scabbard fittings	Colchester	Chichester	Waddon Hill	London	Longthorpe		
Spearheads	Hod-Hill	Cadbury Castle	Kingsholm				

Table 3.1 Main sites in the database for the five most important specific types of equipment (body armour, equine equipment, scabbard, and belt fittings, and spearheads) from the first century AD.

Most of the finds in Table 3.1 date from the mid-first century or the Flavian period and are made of copper alloy, except spearheads, *lorica segmentata* plates and ring armour. Hod Hill and Cadbury Castle could be assemblages for studying iron traditions through mid-first century spearheads, which do not have as long lifetimes as helmets could have had. Both Hod Hill and Cadbury Castle include copper-alloy equipment as well (including equine equipment and *lorica* fittings).

Newstead and Ham Hill offer important quantities of copper-alloy *lorica hamata* scales and there is variety in *lorica segmentata* fittings in Colchester, Chichester, Longthorpe and Cadbury Castle. Newstead will be of interest should material from a slightly later period of time be required in future analysis, as it also has equine equipment.

The Fremington Hagg hoard (Webster 1971) contains just equine equipment, but it is the most important of its kind. The equipment has already being analysed for chemical composition (see Chapter 2).

Colchester has the widest variety in Table 3.1 followed by Chichester and Cirencester, the three having larger number of finds in *lorica segmentata*, belt and scabbard fittings and equine equipment. Colchester, Chichester, Cirencester, Hod Hill and Cadbury Castle could potentially offer variety of equipment in copper alloy mainly, and large assemblages of iron equipment (but only spearheads) in Hod Hill and Cadbury. However, any of the other sites in Table 3.1 could give valuable data if some of the previously mentioned sites are not available.

3.5.2 Biases in the selection of the equipment

The largest bias in the material available in publications seems to be simply how well certain provinces have been studied. This is inherently related to the modern countries within which the Roman provinces are today subsumed. Not only do most of the publications come from Britain and Germany, but also the largest number of sites with published equipment. This is explained not only by the fact that armies were located in the frontier provinces, but also because scholars in these countries have been studying Roman military equipment for centuries. The development of publications in time, in terms of number of publications at least, seems to have behaved in a similar way in each country.

With reference to specific types of equipment to select, it seems reasonable to select specific types of equipment, such as belt-plates, cavalry pendants and *phalerae*, *lorica segmentata* fittings, scabbard plates, or spearheads, as they exist in larger numbers and offer stylistic features to work with as a comparison and as a reference.

3.5.3 Biases in the archaeological record that affect the selection of material for analysis.

Conditions that led military equipment to enter the archaeological record are diverse and not necessarily mutually exclusive. Intentionality, surrounding environment, material and context could all have played a role (see Chapter 2). In addition to these factors the material of which the objects are made is of prime importance. Corrosion in metals will also add bias because these processes affect metals preferentially, as they try to revert to their lowest-energy state as oxides. When compared with copper alloys, iron is less likely to stand the passage of time, unless in an environment where waterlogging has allowed for excellent preservation, such as in Carlisle (Bishop & Howard-Davis 2009), or the equipment found in North Germany and on Danish sites, such as Vimose, Nydam, Ejsbøl and Hjortspring (Jensen *et al* 2003; Ilkjaer 2003; Grane 2007). The nature of the environment also affects preservation, for instance, a saline soil favours corrosion, as exemplified in copper alloys from Masada (Ponting & Segal 1998). In addition, whenever two different metals are in contact, one of them will be preferentially corroded. In the case of copper alloys in contact with iron, the latter would preferentially corrode. For example, in the case of brass, since this is a copper-zinc alloy, the iron would be preferentially corroded over the copper alloy and it would not tend to survive.

However, for Roman military equipment, iron was used mainly for armour plates, some types of helmets, points, and blades. In contrast, copper-alloy objects cover a wider range of military equipment susceptible to change and evolution. Besides, copper-alloy objects are less likely to be heavily corroded when compared to iron artefacts after interacting with the soil for centuries.

The various conditions discussed above certainly affect the perception of the original distribution and extent of the actual equipment. However, the segregating nature of those conditions can also trigger the realization of other independent variables playing a role, or at the very least, they can give us type of objects for representative analysis of the surviving body of evidence.

3.5.4 The assemblages chosen

For this project it was thought ideal to study different types of equipment within a narrow geographical context, or to study equipment from two or three regions of the Empire for the purposes of comparison and to understand its evolution. British and German sites would be the best option for the purpose of statistical relevance when analysing the objects with destructive techniques, but also to see if it is possible to identify individual units, workshops, or traditions through chemical and metallurgical characteristics; a fingerprint. In addition, choosing tight temporal frames for the different sites, could take in account different military units or workshops operating simultaneously in Britain whilst reducing the effects that later recycling may have had on the chemical composition of the metal.

Taking into account the issues discussed above; potential metallurgical traditions within military units in a constrained temporal framework (mid-first century AD but with other earlier and later assemblages for comparison and analysis), the best studied regions (Britain and Germany), the types of objects and materials more likely to survive in the chose regions, the possibility of comparing metallurgical analysis those objects with stylistic analysis, and availability of sampling after negotiation with different museums in Britain and Germany, copper-alloy military objects from the following sites were selected:

- Ham-Hill and South Cadbury (Museum of Somerset);
- Usk (objects in the National Museum of Wales);
- Carlisle (Tullie House Museum);
- Chester (Grosvenor Museum);
- Kingsholm (Gloucester Museum);
- Kalkriese (Varusschlacht Museum).

3.6: Sampling strategy

3.6.1 Sampling methods and sample size

Sampling from a set of artefacts must be understood as the final product of a sequence of sampling mechanisms, most of which are not random that would explain those objects forming part of the archaeological record (Baxter 2003). In this sense, a set of samples from an assemblage cannot necessarily be considered as representative of the universe of objects from which the assemblage comes, regardless of the sample size. However, it is still possible to obtain a statistically representative sample of the assemblage itself.

In practice, obtaining a representative sample for analysis is difficult, as further biases can be introduced in the process of obtaining the sample. Availability of certain objects can be the main obstacle, but also other factors such as the nature of the sampling procedure itself (some objects are too fragile to be drilled, for example), or specific requirements of the analytical technique to be used afterwards: for most techniques metal without oxidation products is required, and this condition may vary due to chemical composition.

In addition to human agency or chemical composition as bias factors for the objects to survive in the archaeological record, other issues such as the geometry of the objects can indirectly cause further bias in the sampling process. Corrosion can be favoured in the presence of heavily worked objects, such as those formed by thin metal sheets, making the possibility of finding uncorroded metal less likely for this type of objects.

For large populations, small random sampling fractions (proportion of sampled objects relative to totality) may be good enough for the sample size to be statistically representative (Baxter 2003: 39-41). In order to have a reasonable statistical estimate, and to achieve comparability between sites, a random sample of ideally a minimum of 20 samples per site was aimed at for the project.

Not only sensitive analysis of each of the samples is required, but also a sound sampling strategy that suggests that the sample is representative of the original artefact. Ideally, a complete artefact would be acquired, so that samples from different sections of it are obtained to form a map of the overall chemical composition. These sections would be compared with the 20 samples mentioned above to analyse how representative of an artefact the latter samples are. However, due to ethical considerations and the requirements of other stakeholders, only one sample could be

taken from each artefact. This sample, if obtained in powder form, by micro-drilling with a 0.5 to 0.8mm drill bit, can only be used for quantitative chemical analysis (AAS). If a sample of solid metal (weighing more than 20mg) from the cross section of the object is obtained, it can be later divided in two, so that one part can be analysed by AAS and the other microscopically examined for structure once it is set in resin. In this way any plating present can also be studied.

Some of the objects analysed were composed of separate pieces, such as joining wires in the case of *lorica squamata* scales, or as remaining pins in *lorica segmentata* hinged plates or in belt fittings. In these cases pins and wires were not sampled or considered for the analysis, as they could have a different composition.

3.7 The analytical techniques used in this project

3.7.1 Atomic absorption spectrometry (AAS)

Broadly speaking, according to Bohr's model, atoms are constituted of a nucleus surrounded by an element-specific number of electrons. The electrons are arranged within different orbitals, which are regions with definite energy. Normally, each element has atoms with their electrons arranged in the lowest-possible energy configuration, or ground state.

Atoms can be excited by absorbing incoming external energy, and temporarily ascend to a higher energy state, or orbital (excitation). However, as this is not the most stable condition, they will descend again to their former state, releasing the previously absorbed energy as a measurable emission (decay). There is not a continuous transition between the different energy levels of an atom; the change is abrupt between them.

As each orbital has its own specific energy values, which translate to equally specific wavelengths, the energy released in the decay process can be associated with the element that emitted it. Each element will emit light at a series of narrow wavelength intervals. The intensity of those bright lines is associated with the concentration of the element (Farnsworth 1986), this relationship being the basis of emission spectrometry. However, the wavelength intervals correspond as well with dark bands (of 0.002 to 0.008 nm width) due to selective absorption by the element in question (Sierner 1986).

These absorption phenomena were observed as early as 1802 and 1814, by Wollaston and Fraunhofer, respectively, but it was not until 1859 that Kirchhoff and Bunsen presented the foundations of spectrochemical analysis (Rubeška & Moldan 1969: 9), when they were able to correlate a band from the absorption spectrum of the sun to the element sodium. The application of

this discovery was initially limited to astrophysics to study the chemical composition of stars (Welz & Sperling 1999: 1). In the mid-twentieth century, a method to introduce a prepared sample as a finely dispersed gas into a flame was developed. This allowed the general application of atomic absorption as a method for absolute compositional analysis (Walsh 1955).

AAS is based on the measurement of the absorption of resonance radiation by free atoms in the gaseous state (Rubeška & Moldan 1969: 13, 29), and thus establishing their concentration. In AAS radiation from a lamp of a wavelength corresponding to the difference of energies between the ground and excited states of the element to be analysed (analyte) passes though the sample in the atomizer (in gaseous from, as free atoms), where some of it is absorbed at wavelengths within their absorption profiles. The source light that is not absorbed in the atomizer passes through a monochromator and then proceeds to a light detector. The output is absorbance, which is a property directly proportional to the concentration of the analyte in the sample solution. Mathematically, absorbance is the logarithm of the ratio of the light intensities measured without (I_0) and with (I) the analyte atoms present in the light path, or $log_{10} \frac{I_0}{I}$: (Sierner 1986).

This analytical technique shows a high sensitivity (in the range of parts per million) for major and minor elements in ancient inorganic materials, such as alloys of copper, tin, lead, silver, and gold, and silicate materials comprising clays, ceramics, glass, glazes and minerals (Hughes *et al* 1976).

AAS is not as sensitive as ICP-MS or NAA, and it is sequential in operation. This means that only one element can be analysed at a time. However, as said above, it is simple, it is operated at a low cost, and its minimum limits of detection suffice for quantifying trace elements present in copper alloys.

Atomic absorption spectrometer

An instrument for AAS is constituted by a lamp, containing the element to be measured, that emits light which passes through an absorption medium. Light sources in AAS should emit intense, narrow, non-self-absorbed resonance lines without continuous background. The most commonly used are hollow cathode lamps, operated at currents ranging between 5 and 30mA (Rubeška & Moldan 1969).

A flame, a chemical reaction between a fuel and an oxidant, is produced in a burner. Air-acetylene and nitrous oxide-acetylene flames are used, so that high enough temperatures are achieved to atomize most elements (Welz & Sperling 1999: 23), since the number of excited atoms varies exponentially with temperature (Walsh 1955).

Eliminating the radiation emitted by the atomizer is necessary. This can be accomplished mechanically by rapidly switching on and off the source radiation with a rotating chopper placed between the source and the sample cell, or electronically, and is referred to as modulation (Beaty & Kerber 2002).Double-beam spectrophotometers, have a rotating chopper provided with mirrors that divides the light beam in two. One of the resultant beams passes through the flame, while the other works as reference. This system eliminates instabilities of the light source emission (Rubeška & Moldan 1969: 74).

The application of AAS in archaeology

AAS was favoured by the scientific community mainly for trace elements analysis, primarily for metals and secondarily for pottery, during the late 1970s to the early 1990s, together with particle-induced x-ray emission (PIXE), nuclear activation analysis (NAA), and later with inductively-coupled plasma atomic emission/mass spectrometry (ICP-AES, ICP-MS). It has been employed in a wide range of characterisation and provenance studies.

AAS began to be widely applied in archaeology after the publication of Hughes *et al* (1976), in which recommendations for sample preparation for different types of materials are presented, as well as minimum limits of detection for a wide variety of elements. Some examples of AAS applications in archaeology are presented below.

In ceramics analysis, AAS is normally used for provenance studies, as with Romano-British pottery (Tubb *et al* 1980), for clustering analysis of Hellenistic and Roman fine pottery from Benghazi (Hatcher *et al* 1980), the chemical analysis of sherds in early Iron Age Cyprus (Brodie & Steel 1996), and to establish the provenance of seventh to third century BC pottery in Italy (Rottuno *et al* 1997).

In lithics analysis the application is similar: AAS was used for elemental characterization of obsidian from Alaska as a standard reference material for provenance studies (Wheeler & Clark 1977), to quantify metallic trace elements in Neolithic flint tools (Craddock *et al* 1983). It was used for the identification of the sources of the stone of the Cathedral of Seville (Bello & Martín 1992) and in conjunction with ICP-MS to analyse vitreous rocks exploited in the Formative period (first millennium BC) of northern Chile (Seelenfreund *et al* 2009).

In the case of metals, AAS has been used for both characterization and provenance analyses (also see Chapter 2): for example, by Craddock *et* al (1973) to establish whether harness fittings from different museums belonged to the Fremington Hagg hoard, by Hughes (1979) to quantify fully the chemical composition of leaded Bronze Age copper alloys, to quantify and establish the origin of gold and silver in artefacts from Sarawak, Indonesia (Fabris & Treloar 1980), to characterize

orichalcum coins, in conjunction with other analytical methods (Carter *et al* 1983). It has been employed to explore medieval copper-alloy production in West Africa (Craddock & Picton 1986) and to analyse the chemical composition of Greek early Bronze Age metals (McGeehan-Liritzis & Gale 1988). It has been used to measure major elements in metalwork from a Phoenician settlement in Spain (Giumlia-Mair 1992), as a comparative analytic technique in the re-analysis of the Chalcolithic Nahal Mishmar Hoard (Shalev & Northover 1993), in a study of early Bronze Age tin processing and provenance in Göltepe (Earl & Özbal 1997) and more recently to analyse ancient South Arabian leaded-bronzes (Chiavari *et al* 2011).

AAS has been applied less frequently to other materials. Examples include measurement of the lead content in Romano-British human bones (Waldron *et al* 1976), the trace elements in excavated human bone in the Middle and Late Woodland Sites in Illionis (Lambert *et al* 1979) and to measure lead, cadmium and zinc traces in Romano-British teeth (Whittaker & Stack 1984).

In recent times, it has been often used in conjunction with other techniques, such as ICP-MS or NAA or as a comparative tool. The authors almost always report close agreement between the different techniques and AAS.

3.7.1.1 Methodology for AAS in this project

This thesis mainly followed the guidelines for analysis of copper-alloy artefacts suggested by Hughes *et al* (1976) which account for specific problems pertaining archaeological material.

Analytical sensitivity

The sensitivity of the instrument is its response to a specific concentration of the analyte. Ensuring suitable estimates for analytical sensitivity should be the first step in the analysis, as this represents the baseline operative conditions of the instrument for the entire analysis. Calibration curves will rely upon the sensitivity of the instrument for determining the concentration of an element.

Sensitivity can be altered by regulating the amount of solution aspirated by adjusting the nebulizer, fine tuning the monochromator, altering the proportion of the mix of gases to produce the flame, the utilization of an impact bead, or by changing the geometry of the lamp-detector array (moving the burner, or the lamp inclination).

Whenever the sensitivity check value was below the reported conditions in the manual, instrumental parameters were optimized, subject to availability. This was apparent when analysing tin and arsenic, two elements with relative poor sensitivities in AAS (see below).

The spectrometer, an air-acetylene flame operated Perkin Elmer 3110 is remotely controlled by proprietary software, AA WinLab Ver. 3.2, whose main purposes are to take control of certain configuration parameters, and to generate the calibration curve from aspirating standard solutions, and to manage the sequence of analysis: delay time (time the spectrometer aspirates the solution without analysing it), integration time (time of effective analysis), and number of replicates (see below).

Standard solutions for calibration

Before the samples are digested in acids, they ideally have to be thoroughly cleaned of oxidation products, since these cannot be assumed to contain a similar chemical composition to that of uncorroded metal of the interior (Hughes *et al* 1976). Whenever the size of the sample allowed for it, corrosion products were mechanically cleaned using a sharp scalpel. Total removal of corrosion products is sometimes not possible when intergranular corrosion is present in the samples or when the sample consists of powder only. Since some corrosion products cannot be dissolved in aqua regia, the analysis of corroded samples can produce low summed totals. This problem can sometimes be compensated for by normalising the totals at the end of the analysis, but accuracy for trace element quantification can suffer as a result.

The sample dissolution for this project was done as Hughes *et al* (1976) recommend:

- Weigh 10 to 20mg of copper-alloy drilling to ±0.02mg
- Quantitatively add 2.5 ml of aqua regia (one part HNO_3 to three parts HCl)
- Place on a hotplate (<60^{o}C)
- Transfer quantitatively to 25ml graduated flask
- Dilute to volume (25ml) with ultra-pure (> 80.2 MΩ) water

It is important that the matrix, or the major component of the solution, is the same for both standards and samples, so that differences in elemental sensitivity and interferences are minimized (Pollard *et al* 2007: 303). AAS is less prone to inter-element effects compared with emission methods (Walsh 1955). However, Hughes *et al* (1976) discovered that if the sample contained a lot of copper, this could alter the readings of other metals in such a way that they appear over-represented in the sample. The elements with their increments are as follows: tin (10%), lead (8%), zinc (8%) and silver (10%). This must be taken in to account, as the increment is over the analytical precision capability. To compensate for matrix effects when analysing copper alloys with AAS a series of standards encompassing the range of concentrations for the elements to be measured has to be prepared.

These standards have to be continually interpolated between samples to minimize matrix effects (Gilmore & Ottaway 1980).

Hughes *et al* (1976) proposed two remedies for the problem, the first involving a constant correction to the readings obtained. The second consists in adding a fixed amount of copper to the standard solutions used for calibration. The latter approach was followed for this project.

At least two standard solutions should be prepared for calibration. Taking advantage of the fact that broad compositional ranges will be already known from other studies of Roman alloys, the first solution could contain a concentration below that expected for the sample, while the second will have one above it. However, the spectrometer still needs a reference defining the absence of the element to be measured. This is provided by a blank solution, prepared in the same manner as the sample solution.

This set of three solutions (blank, lower standard and higher standard) will define a calibration curve. Throughout the analysis, the blank and the standard solutions were periodically checked between sample runs to ensure that the spectrometer drift remained minimal.

Care was taken to ensure that the low concentration solution for calibration lay entirely within the dynamic linear range reported for the instrument in the manual. All volumetric transfers were carried out with Grade A Pyrex glassware.

Since the aspiration rate depends on the viscosity of the solution that is being sprayed in the AAS unit (Ebdon *et al* 1998), blank solutions need to have similar viscosity values to those of the standard reference materials, standard solutions for calibration curves, and sample solutions, in order to minimize nebulizer uptake interferences. This was achieved by keeping the percentage of aqua regia constant.

Standard reference materials

Even when having a calibration curve made from standard solutions, standard reference materials used as samples during the analysis are essential to account for any drift during the analysis or after it. The standard reference materials used in this thesis contain similar matrices to those from the objects in the archaeological record. The standard reference materials were used as control in this project can be seen below (see Tables 3.2 and 3.3).

Element	BNF C71x07	MBH B22	BAM 211	GM4
Al	0.002	0.207		<0.002
Si	0.005	0.15		<0.005
P	0.008	0.140	0.0267	<0.005
S		0.135	0.0211	0.33
Mn	**0.01**	**0.147**	**0.0019**	**(0.0019)**
Fe	**0.08(0)**	**0.098**	**0.11**	**0.051**
Ni	**0.51**	**0.179**	**0.122**	**2.05**
Cu	**Remainder**	**83.4**	**87.71**	**82.6**
Zn	**5.2**	**14.6**	**0.56**	**7.17**
As	**0.20**	**0.136**	**0.0213**	**0.021**
Se			0.00114	
Ag			**0.059**	**0.0062**
Cd			0.00144	
Sn	**6.1**	**0.186**	**10.6**	**2.5**
Sb	**0.22**	**0.173**	**0.033**	**0.042**
Pb	**4.0**	**0.146**	**0.74**	**5.2**
Bi	0.01(8)	0.22	0.002	0.041

Table 3.2 Chemical composition of standard reference materials used.

Element	BNF C71x07	MBH B22	BAM 211	GM4
Ag			*	
As	*			
Co				
Cu			*	*
Fe		*	*	
Mn		*		
Ni		*		
Pb	* (high)	* (low)		* (high)
Sb	*			
Sn	*		*	*
Zn		*		*

Table 3.3 Standard reference materials used by element.

Sample preparation

The samples were weighed and put into 25ml vials, which had also been previously weighed. The samples were then digested by means of a 2ml addition of aqua regia, 3:1 hydrochloric acid-nitric acid ($HCl:HNO_3$), for 20 minutes on an electronically controlled hotplate set for a target temperature of 58°C, and then left to stabilize before heating up the samples. Heating at a higher temperature would favour the formation of metastannic acid, as the tin comes out of solution (Hughes *et al* 1976).

The vials with the digested samples were then filled to approximately 25ml and weighed again to obtain the weight of the solution by subtracting the weight of the empty vial from the total weight of the vial now containing the solution. Recording the weight of the sample and that of the solution allows for calculating the dilution factor of each sample in each solution. This factor is multiplied by the reading obtained by the AAS to produce a percentage value of the element in the sample. The dilution factor is also used to calculate the limit of detection of each element in each sample solution.

For some samples it was not possible to obtain the ideal weight of 15 to 25mg. For low weight samples, solutions of 10ml were obtained, with aqua regia in the same proportion as the

25ml solutions. The accuracy of this procedure was first tested for all the elements analyzing standard reference materials. With this method it is possible to analyze accurately samples with weights as low as 10mg. Samples with lower weights though, with weights of 5 or 6mg, introduce important errors when calculating trace elements, and should be reliable only for qualitative analysis, or alloy-type identification.

Sequence of analysis

Analysis of the object samples was done within a few days of preparation of standards solutions for calibration to avoid degradation of some constituents in the solutions, such as the formation of tin oxide (Hughes *et al* 1976).

The first step was warming up the lamp for the element to be analyzed and selecting the right wavelength in the monochromator. The sensitivity check was run next with solutions of a known amount of the element in question. To improve the response the burner can be slightly rotated and the nozzle controlling the amount of liquid being aspirated can be adjusted.

Before any reference is introduced to the instrument in the form of a calibration curve, the AAS measures its response to absorption in the form of arbitrary absorbance units. A characteristic concentration check represents the concentration at which 0.2 absorbance units (from a range of 0 to 1) are obtained. For all the analysed elements, except tin and arsenic (see below) the response was above the characteristic concentration to obtain 0.2 absorbance units reported by the manufacturer (see Table 3.4).

Once the sensitivity check was approved the next step was building a calibrating curve. For this, the instrument has to be informed of what constitutes a baseline for measurement, which is provided by the aspiration of blank solution. Then the two standard solutions were aspirated and considered as points for a calibration curve by the analysis software.

After the calibration curve was obtained, the blank solution was aspirated for testing relative to the newly formed curve. The analysis of a standard reference material followed, and immediately quantified in terms of percentage. A new calibration curve was calculated whenever a deviation larger than 10% from the SRM was found.

Element	Wavelength (nm)	Characteristic concentration check (mg/L)	Linear range (mg/L)
Ag	328.1	2.5	4
As	193.7	45	100
Co	240.7	7.0	3.5
Cu	249.2	300.00	100
Fe	248.3	5.0	6.0
Mn	279.5	2.5	2.0
Ni	232.0	7.0	2.0
Pb	283.3	20.0	20.0
Sb	217.6	25.0	30.0
Sn	286.3	150.0	400.0
Zn	213.9	1	1.0

T**able 3.4** Sensitivity check. Characteristic concentrations for obtaining a response of 0.2 absorbance units at a specific wavelength (at standard conditions) and linear range for each element analysed, according to the instrument manufacturer.

Every 5 to 10 samples the blank was checked to correct any drift or memory effects that could have arisen during the analysis. If any problem was detected, the software was informed by the user that a blank was being analysed, so that the subsequent batch of five samples was comparable to the previously analysed ones.

3.7.1.2 Considerations for specific elements

Some important considerations and particular care should be taken for some elements for different specific reasons at different stages of the analysis and involving solubility, low sensitivity issues, or the utilisation of a different absorption line according to the concentration that is to be measured. In the case of tin and arsenic, a series of tests were devised to establish lower limits of detection at the experimental conditions used in all the sample analyses.

Silver

There is an important consideration when preparing the stock solutions and the standard solutions for calibration with regard to silver. Whenever silver is added to a solution, acids should be present to avoid part of the silver precipitating, which could lead to important errors in the analysis. When preparing the stock solutions from which the standards solutions for calibration are prepared, using any agent containing chlorine (such as hydrochloric acid), no more than 6 ppm of silver can to be added, as precipitation of silver chloride will otherwise occur. For this project, 1ml of 1000 ppm Ag standard concentrate was added to the stock solution, resulting in a 5 ppm concentration. This guaranteed that less than 6 ppm were dissolved in the standards solutions for calibration

Cobalt

Since cobalt was not present in the standard reference materials used for the rest of the elements, solutions with specific concentrations were prepared from standard reference concentrates. The solution contained 500 ppm of copper to account for matrix effects on cobalt in the presence of copper.

Zinc

Zinc was measured with a hollow cathode lamp at a wavelength of 206.2nm. Due to the very high response of the instrument for measuring zinc, the signal was saturated for the range of dilution of the samples. To account for this the burner was first rotated. However, since this action was not enough to decrease the response of the instrument, further dilution was tried for analyzing zinc only.

After the dissolved samples were weighed, aliquots of 2ml were taken from each sample vial into new vials to make up a solution of 25ml (adding 2ml of aqua regia and 21ml of ultra pure water). This procedure solved the problem of high sensitivity while introducing a further 12.5 dilution factor. However, the method proved adequate, as standard reference materials were tested

as samples with the same method and successfully quantified. Furthermore, in a similar way to tin, zinc was measured primarily as a means of identifying alloy type, and not as a trace element. In order to measure these new dilution levels of zinc, the concentration of zinc present in the solutions for calibration had to be reduced accordingly.

Lead

Lead along with zinc and tin, is one of the main elements considered to define alloy type in Roman metallurgy. It is regarded as such for this project and analysed mainly as a minor or in some cases major constituent. All the objects analysed were considered to have low levels of lead (much less than 1%) before AAS analysis, since the majority of the objects analysed belong to the first century AD, and they do not normally contain a significant amount of lead. Lead concentrations associated with these objects lie well within the linear range of the instrument sensitivity response to lead for the 283.3 nm absorbance line.

Those samples from objects with higher lead concentrations were run again, but with the monochromator tuned to a different wavelength, 261.4 nm, and a different calibration curve to take in account higher lead values. For this analysis a different standard reference material containing lead as a major constituent was used (C71x07, see Tables 3.2 and 3.3).

Tin and arsenic

A series of tests was carried out aiming to determine the minimum measurable concentrations of tin and arsenic by AAS when the samples from Cadbury Castle, Ham Hill, Usk and Carlisle were analysed, and for subsequent analyses. These concentrations were measured by varying certain operational parameters of the instrument. Arsenic and tin were selected because they are known to have poor sensitivities and instabilities in AAS relative to the other elements analysed in this project.

First, the experimental conditions for the analysis of the archaeological samples were replicated by measuring solutions with known concentrations of the element and establishing the minimum quantity that could be detected. Then, additional tests were run, in which specific instrumental parameters were altered to look for an even lower value. For running the tests, four parameters affecting the sensitivity of the instrument toward specific elements were changed in total. Three are related to aspirating the solution and the fourth one is the composition of the flame.

Identical standard solutions were created to construct calibration curves. As the alloys analysed in the project are all copper based, and copper interacts with other elements to produce

enhanced or diminished readings (matrix effect), copper has to be added in all the solutions. In this way it is made sure that the matrix effect affects all the solutions.

The instrument allows for controlling certain parameters of the aspirating process. One of them is delay time; a period of time in which the instrument aspirates the solution to be measured but no actual reading is taken. This time accounts for any instabilities or sudden peaks in readings in the transition between samples or from a blank solution to a sample. A second time parameter tested is integration time, when solution is being aspirated and analysed by the instrument. The number of times the solution is analysed, or replicated, was the third parameter.

Air is used as both a carrier gas and as oxidant in combination with acetylene to produce a flame that breaks the components in the solution. Changes in the ratio of air to acetylene affect the sensitivity of the instrument for detecting specific elements. Composition of the flame was altered in the tests run to detect arsenic.

Tin

A stock solution was prepared by adding 10ml of 10,000 ppm of standard concentrate copper solution and 10ml 10,000 ppm of tin solution to a 200ml flask and filling with ultra-pure water. The resultant stock solution contained both 500 ppm of copper and tin. Two standard solutions containing 50 and 200 ppm were created from the stock solution by extracting 10ml and 40ml, respectively, to 100ml flasks, adding 8ml of aqua regia and filling with ultra-pure water. Four additional solutions were prepared to be tested as samples once a calibration curve was obtained with the standard solutions. These four test solutions (1, 2, 5 and 10 ppm) were prepared from the standard solutions and contained copper and 8ml of aqua regia to match the matrices of both the standard solutions and the dissolved samples from the archaeological objects. Since the standards solutions contain 50 and 200 ppm, respectively, the test solutions lie within the lower part of the calibration curve. However, the values of 50 and 200 ppm are meant to include all the spectrum of possible copper-tin alloys as a way of indicating alloy type, rather than quantifying traces of tin.

The first part of the test included warming the Sn lamp to ensure maximum beam stability. The wavelength chosen was 286.3 nm, as it offers the best compromise between a relatively low characteristic concentration check (150 ppm) and background noise. Standard conditions published by the spectrometer manufacturer, Perkin Elmer (1996), show a value of 150mg/L for obtaining the characteristic concentration check of 0.2 absorbance units. For obtaining these values the recommended flame is nitrous oxide and acetylene, and an electrodeless discharge lamp (EDL), neither of which was available.

Both for these tests and the artefact analyses, hollow cathode lamps (HCL) and an air-acetylene gas mixture were used. Additionally, a flow spoiler and an impact bead, which improves the instrument sensitivity, in general, were used at all times. The nozzle controlling how much solution is aspirated and the burner position relative to the beam were adjusted to maximise sensitivity when aspirating the solution containing 200 ppm (stock solution). The characteristic concentration check values during the tests averaged 0.06 absorbance units for this solution. A value higher than 0.2 would have been expected according to the manufacturer's AAS standard conditions for tin. However, they acknowledge that using a HCL lamp and an air-acetylene flame reduce sensitivity for tin.

Seven tests were run for tin, varying four parameters, as summarised in Table 3.5. For each test a calibration curve was produced using the standards solutions prepared. When constructing each curve, measurements were taken with the individual parameters for each test.

Test 1 represented the values of the parameters as they were set when analysing the archaeological samples from South Cadbury, Ham Hill, Carlisle and Usk. The 1, 2, and 5 ppm solutions were not detected and the variation between replicates was high. For Test 2 the delay time was doubled. This contributed to an increase in sensitivity and also a slight increase in precision. This time the 5 ppm solution was the lowest detected. For Test 3 the integration time was set from 1 to 1.5 seconds, but a significant effect was not observed. For the following test, No. 4, integration time was increased to two seconds and the 2ppm solution detected and higher precision was observed. Expectedly, with high integration and delay times, Test 4 showed the best results in precision and stability amongst Tests 1 to 6. However, it utilises more solution, and another 10 elements including arsenic (which also uses higher amounts of solution) have to be measured having 20 ml of solution in the best scenario. Besides, tin was not measured as a trace element, but as a major element for alloy-type classification of Roman military equipment. For these reasons a compromise between the amount of solution used and sensitivity was required. In Test 5 and Test 6 the integration time was reduce to 1.5 and then further to 1.3, respectively without significant differences between them. The 2 ppm solution could still be detected, but the readings were very instable.

In Test 7, the replicates were increased from 3 to 5, and the integration time set to 1.5. This combination proved to be the best. However the additional delay time of 7 and the two extra replicates would use an even higher amount of solution.

Test 6 was chosen as the combination of parameters to use for the following sample analyses, as it constitutes a definite improvement on Test 1 and yet enough to measure tin as a major or minor element for alloy-type classification.

Based on the seven tests, the lowest tin content detected in solution was 10 ppm (Test 1), and a minimum 2 ppm concentration was considered for Chester, Kalkriese and Kingsholm with the experimental parameters reconsidered.

Tin	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Delay time (s)	5	10	10	10	7	7	7
Integration time (s)	1	1	1.5	2	1.5	1.3	1.5
Replicates	3	3	3	3	3	3	5
Fuel in flame	2	2	2	2	2	2	2
Oxidant in flame	3.5	3.5	3.5	3.5	3.5	3.5	3.5
1 ppm sol. average	ND	ND	ND	ND	ND	ND	ND
2 ppm sol. average	ND	ND	ND	5.2	1.3	4	2.5
5 ppm sol. average	ND	5.8	3.8	7.5	8.3	3.45	5.1
10 ppm sol. average	11.6	13.6	7.5	11.9	11.5	11.6	8.1

Table 3.5 Summary of the tests for establishing the minimum detectable concentration of tin by AAS in this project.

Arsenic

A similar methodology to tin was implemented for establishing limits of detection for arsenic. This time, however, since measuring arsenic as a trace element was desirable, an additional parameter was introduced. This was the composition of the flame, which remained constant for the tin tests described above. The instrument manual from the manufacturer recommends a reducing (slightly yellow and rich) flame for measuring arsenic (Perkin Elmer Inc 1996). A more reducing flame can be achieved by increasing the amount of fuel in the flame.

Similar to the analyses of the artefact samples, a calibration curve was constructed from a 2 ppm and a 8 ppm arsenic solutions in aqua regia and ultra-pure water, taking 4ml and 10ml from a 200 ppm As stock solution (20 ppm) that had been prepared from a 1000 ppm standard solution. This calibration curve was used to test three arsenic solutions containing 1, 4, and 6 ppm.

According to the manufacturer, the characteristic concentration check at a wavelength of 193.7 nm (which represents the best compromise between sensitivity and noise), using an EDL lamp (an HCL lamp produces poorer results, by as much as 25%) and a reducing air-acetylene flame is 45mg/L. After adjusting the nebuliser and the burner position, 0.07 absorbance units for a concentration of 20 ppm were obtained. Since the instrument sensitivity has a linear range up to

100mg/L, the sensitivity obtained is 80% of that of the standard conditions reported by the manufacturer. This is within the 25% decrease of sensitivity introduced by the use of an HCL lamp instead of an EDL lamp.

Arsenic	**Test 1**	**Test 2**	**Test 3**	**Test 4**
Delay time (s)	10	10	10	10
Integration time (s)	1	1.3	1	1
Replicates	3	3	5	5
Fuel in flame	2	2	2	3
Oxidant in flame	3.5	3.5	3.5	3.5
1 ppm sol. average	0.9	1.1	2.0	ND
4 ppm sol. average	5.09	5.6	3.0	3.0
6 ppm sol. average	9.3	9.5	7.5	4.3

Table 3.6 Summary of the tests for establishing the minimum detectable concentration of arsenic by AAS.

Test 1 was run in the same conditions that the solutions from the artefacts samples underwent, with 1 second of integration time after a 10 second delay time. This repeated three times (Table 3.6) and with no change in flame composition. For Test 2 the integration time was slightly increased from 1 to 1.3, but no significant changes were observed. For Test 3 the integration time reverted to 1 second and replicates were increased from 3 to 5, which brought higher precision to the results and slightly higher accuracy for the 4 and 6 ppm solutions. For Test 4 the composition of the flame was altered by increasing the amount of fuel until an even and slightly yellow flame was obtained. With these parameters 2 ppm seems to be the lowest measurable concentration (measured at an average of 1.49 from the standard solutions).

Altering the composition of the flame noticeably improved the stability of the readings but slightly decreased sensitivity. Test 4 produced the most reliable results amongst the four tests, and its parameters were chosen to be used to analyse subsequent artefact samples, as arsenic is required to be measured at trace levels.

It can be said that concentrations over 1 ppm in solution can be detected with the experimental conditions described above.

3.7.1.3 The limits of detection

Both precision and accuracy suffer when limits or detection are approached. The detection limit of an element for AAS is defined as: "the concentration which will give an absorbance signal three times the magnitude of the baseline noise" (Beaty & Kerber 2002: 7). To calculate the noise, the standard deviation of the values for 10 replicates of an analytical blank solution was obtained (denoted by σ). For fully quantitative analysis then, a level of 3σ is required. However, limits of detection at levels less than 3σ can still be used for group analysis or for semi-quantitative analysis.

The limits of detection for all the elements used in this project can be seen in Table 3.7, where the general results are expressed in ppm for each batch of analysis. Within each batch, a sample has its own limit of detection per element when expressed as percentage, as its dilution factor is different to the others samples.

ppm 1σ										
Batch	**Pb**	**Sn**	**Zn**	**Ag**	**Fe**	**Ni**	**Co**	**Mn**	**Sb**	**As**
Ham Hill and South Cadbury	1.94	0.83	0.03	0.01	0.09	0.02	0.04	0.01	0.08	0.76
Usk and Carlisle	0.76	0.83	0.03	0.02	0.16	0.10	0.15	0.05	0.46	0.52
Chester	0.22	0.83	0.03	0.005	0.08	0.02	0.04	0.01	0.11	0.54
Kingsholm and Kalkriese 1	0.36	1.34	0.10	0.004	0.04	0.03	0.07	0.01	0.12	0.97
Kingsholm and Kalkriese 2	0.18	1.00	0.19	0.005	0.03	0.02	0.02	0.02	0.10	0.54
Kingsholm and Kalkriese 3	0.32	0.33	0.11	0.01	0.02	0.03	0.05	0.01	0.10	0.45
Kingsholm and Kalkriese 4	0.58	0.83	0.14	0.01	0.05	0.01	0.03	0.01	0.12	0.46
Mean	**0.62**	**0.86**	**0.09**	**0.008**	**0.068**	**0.035**	**0.058**	**0.018**	**0.16**	**0.61**

Table 3.7 Limits of detection (ppm) for each of the elements used in AAS analysis of the samples.

3.7.1.4 Correspondence of analysed standard reference materials with certified values

As explained above, standard reference materials were analysed as unknowns to test the AAS calibration curves by testing the results with certified values. Values were obtained for different standard reference materials for each batch: Ham Hill and South Cadbury, Carlisle and Usk, Chester, Kalkriese and Kingsholm. Table 3.8 show these values and their associated mean, error, and precision for the different standard reference materials used in this project.

	% Ag	% As	% Co	% Cu	% Fe	%Mn	% Ni	% Sb	%Sn	% Zn	%Pb
211, certified	**0.059**	0.0213		**87.7**	**0.11**	0.0019	0.122	0.033	**10.6**	0.56	0.74
HamH-CC	0.061								9.049		
HamH-CC	0.061								8.719		
HamH-CC	0.057										
CSL-USK	0.071			88.8	0.128						
CSL-USK	0.062			87.7	0.106						
Chester	0.056			89.5	0.128						
Chester	0.055			92.9	0.114						
KK - Kingsholm 1	0.056			85.4	0.107						
KK - Kingsholm 1	0.052			83.8	0.101						
KK - Kingsholm 2	0.053			81.5	0.108						
KK - Kingsholm 2	0.045			79.4	0.111						
KK - Kingsholm 3	0.062			92.7	0.113						
KK - Kingsholm 3	0.061			90.3	0.127						
KK - Kingsholm 4	0.056			88.3	0.100						
KK - Kingsholm 4	0.052			87.1	0.101						
Mean	0.057			87.3	0.112				8.884		
Std. Dev.	0.006			4.1	0.010				0.234		
Error %	3.4			0.5	1.8				16.2		
Precision	10.7			4.7	9.2				2.6		

	% Ag	% As	% Co	% Cu	% Fe	%Mn	% Ni	% Sb	%Sn	% Zn	%Pb
B22, certified		0.136		83.4	**0.098**	**0.147**	**0.179**	0.173	0.19	14.6	0.15
HamH-CC					0.134	0.116	0.165				
HamH-CC					0.133	0.122	0.171				
CSL-USK						0.152	0.187			13.8	0.21
CSL-USK						0.155	0.176			14.1	0.21
Chester						0.137	0.166			16.0	0.15
Chester						0.146	0.172			16.8	0.17
KK - Kingsholm 1						0.130	0.159			14.7	0.17
KK - Kingsholm 1						0.167	0.158			15.2	0.17
KK - Kingsholm 2						0.136	0.147			16.1	0.18
KK - Kingsholm 2						0.161	0.142			16.3	0.15
KK - Kingsholm 3						0.141	0.150			16.2	0.16
KK - Kingsholm 3						0.139	0.157			15.9	0.13
KK - Kingsholm 4						0.123	0.148			15.7	0.21
KK - Kingsholm 4						0.123	0.144			15.2	0.17
Mean					0.13	0.14	0.16			15.51	0.17
Std. Dev.					0.001	0.02	0.01			0.91	0.03
Error %					36.6	5.4	10.5			6.2	18.2
Precision %					0.6	11.3	8.4			5.9	15.1

Table 3.8 Correspondence of standard reference materials analysed as unknowns and certified values

(continues on next page).

	% Ag	% As	% Co	% Cu	% Fe	%Mn	% Ni	% Sb	%Sn	% Zn	%Pb
GM4	0.0062	0.021		**82.6**	0.051	0.0019	2.05	0.042	**2.5**	**7.17**	**5.2**
HamH-CC				75.8					2.163	7.2	5.4
HamH-CC				63.6						7.1	6.0
HamH-CC											4.2
HamH-CC											6.4
HamH-CC											6.2
Mean				69.7						7.14	5.64
Std. Dev.				8.7						0.12	0.9
Error %				15.6						0.4	8.5
Precision %				12.5						1.7	15.9

	% Ag	% As	% Co	% Cu	% Fe	%Mn	% Ni	% Sb	%Sn	% Zn	%Pb
C71x07		**0.2**			0.08	0.01	0.51	**0.22**	**6.1**	5.2	4
HamH-CC		0.45						0.14			
HamH-CC		0.45						0.12			
HamH-CC		0.15									
CSL-USK		0.14						0.24	5.9		4.04
CSL-USK		0.32						0.18	7.4		3.52
Chester		0.14						0.18	6.5		4.12
Chester		0.17						0.22	6.2		4.00
KK - Kingsholm 1		0.22						0.21	5.5		4.08
KK - Kingsholm 1		0.29						0.21	6.1		
KK - Kingsholm 2		0.21						0.21	5.8		3.70
KK - Kingsholm 2		0.18						0.19	6.0		3.75
KK - Kingsholm 3		0.21						0.19	6.3		4.03
KK - Kingsholm 3		0.20						0.23	6.4		4.27
KK - Kingsholm 4		0.21						0.223	6.2		
KK - Kingsholm 4		0.20						0.240	6.3		
Mean		0.23						0.20	6.22		3.95
Std. Dev.		0.10						0.04	0.47		0.24
Error %		17.1						9.6	1.9		1.4
Precision %		42.3						18.1	7.5		6.0

Cobalt 1ppm	**% Co**
HamH-CC	
HamH-CC	
CSL-USK	1.09
CSL-USK	0.82
Chester	0.88
Chester	0.85
KK - Kingsholm 1	1.02
KK - Kingsholm 1	1.13
KK - Kingsholm 2	1.02
KK - Kingsholm 2	1.07
KK - Kingsholm 3	1.03
KK - Kingsholm 3	0.96
KK - Kingsholm 4	0.96
KK - Kingsholm 4	0.94
Mean	0.98
Std. Dev.	0.10
Error %	1.9
Precision	9.9

Table 3.8 Correspondence of standard reference materials analysed as unknowns and certified values

(continues from previous page).

There is an adequate agreement between certified and measured values for trace element analysis. Precision for arsenic is the lowest (highest relative standard deviation: 42%), as expected, but significantly improves for other trace elements: antimony, nickel, and silver (RSD of 18, 8 and 11%, respectively). In all cases the error for trace elements is less than 20%, the maximum being 17% for arsenic, a notoriously difficult element to analyse by AAS. An expected accuracy of ±15% for trace elements is reported (Hughes *et al* 1976).

3.7.2 Scanning electron microscopy with energy dispersive spectrometry (SEM-EDS)

Scanning electron microscopy and energy dispersive x-ray spectrometry (EDS) are part of both the micro-structural and qualitative and semi-quantitative characterization of the copper-alloy objects being analysed in this project. But first it is necessary to give a brief description of the physical principles underlying these analytical techniques.

3.7.2.1 Interactions of electrons with matter

Scanning electron microscopy is a very powerful analytical tool, as it can provide structural and compositional information with the additional benefit of being virtually non-destructive to the sample.

When a beam of electrons (primary electrons) strikes a specimen several phenomena take place within an interaction volume of atoms, this being the region into which those electrons penetrate. Atoms scatter incoming electrons upon impact in probabilistically different ways that depend on the original energy of those electrons and the particular atoms with which they are interacting (Goodhew *et al* 2003). Different signals can be picked up then, some of them involving original electrons and some other electrons from the specimen, and later converted to images. Other interactions can produce x-rays, which can be measured by specialized detectors and later interpreted as chemical footprints for the presence of elements. Amongst the effects caused by the interaction of electrons with matter, three are of special relevance for this study: backscattered electrons, secondary electrons and x-rays.

Scattering of electrons can be elastic or inelastic as they interact with the sample. In the elastic type, the electron trajectory is altered while the energy remains almost constant, as the nucleus of the atom has a much greater mass compared to that of the electrons (Glauert 1974: 83). On the other hand, inelastic scattering involves, at least, a reduction in the velocity of the electron and a transfer of energy from it to the atoms of the sample (Newbury 1986: 2).

The energy transferred in inelastic scattering is in the form of heat mainly. However, a small amount may escape in the form of x-rays, secondary electrons, or light amongst other types of radiation.

3.7.2.2 X-rays, secondary and backscattered electrons

Primary electrons can cause secondary effects that can be detected outside the specimen. For instance they transfer energy to some electrons in the surface region of the sample causing them to escape from it. Secondary electrons are abundant and constitute the main signal for imaging in the scanning electron microscope (Goodhew *et al* 2003: 34). Secondary electrons originate within the upper-most region of the sample volume, providing the best signal for topographic imaging.

Most of the primary electrons are stopped by the solid specimen. The interaction volume of the electrons with the sample refers to the space where 95% of them have been halted. However, a few of them leave the specimen. Backscattering is the deflection of a primary electron by an elastic scattering process through an angle greater than 90° relative to the incident direction, followed by propagation back through the surface of the specimen. In a solid sample, multiple scattering allows for electrons with lower scattering angles to be detected as well (Newbury 1986: 11). However the detected backscattered electrons are not as numerous as secondary electrons.

Since the detected backscattered electrons interact in regions near the surface, within the upper regions of the interaction volume, they can provide a high spatial resolution, although not as great as that of secondary electrons (Goodhew *et al* 2003: 127).

Since the signal response of backscattered electrons is a function of the atomic number of the atom in the sample with which the incident electrons interact, it is possible to produce an image that shows contrasts between different elements. Since elements with a higher atomic number show a stronger response to backscattering electrons they appear brighter in the images. Backscattered electron images are very useful to detect the presence of phases or coatings that could have remained hidden when producing an image in normal mode (secondary electron).

Atoms can be schematically viewed as a positively charged nucleus surrounded by a number of negatively charged electrons, neutralizing the charge. Electrons in turn are arranged in states, or ‘shells’ (K, L, M) of which the innermost, those in M, are the most tightly bound to the nucleus.

Incoming primary electrons can excite atoms from the sample by knocking localized electrons (associated with an atom) out of them. As the natural tendency is that of relaxation, the atom will release the excess energy in different ways, depending on how external the shell from

which the ejected electrons came. As an example, if a K electron were knocked out, an electron from a more external shell, L, could occupy the vacant state left in the K shell. In doing so, it would emit an x-ray of $K_{\alpha 1}$ or $K_{\alpha 2}$ energy, characteristic of the atom species the electron came from. Thus, x-ray signals can be used to determine the presence of specific elements.

The volume of the sample contributing to the x-ray signal is of the order of the interaction volume, this implies several micrometres in diameter (Goodhew *et al* 2003: 126).

3.7.2.3 Scanning electron microscopy

In optical light microscopy, refraction occurs as a light wave passes from one medium (the air) to another (the lens). This involves a definite change in the direction of the light rays and a change in the velocity of the light wave, which depends on the particular physical properties of each medium, reflected on the refractive index (Geiss & Romig 1986).

In the case of the electron microscope the same geometric principles apply when firing a beam of electrons toward the specimen. The difference is in the nature of the lenses, which are electromagnetic, and the electron beam monochromatic; single wavelengths given by the filament and defined by the accelerating voltage (Phillips 1971: 147).

The beam of electrons is produced by an electron gun, usually a tungsten filament, as the electrons are accelerated by a potential difference of 1 to 30 KeV (Goodhew *et al* 2003: 122). Below the electron source, two electromagnetic condensers control the diameter of the beam so that the area of the specimen that the beam hits can be regulated. These are followed by the objective lenses and scan coils.

The focal length of these lenses depends on the force of the magnetic field, which is changed by varying the current passing through a coil of wire. In the SEM, electromagnetic fields are used to deflect the entire beam, so that it can be scanned back and forth (Goodhew *et al* 2003: 29).

Since electron scattering is much more strongly affected by the presence of gases than light waves are, electron microscopes have to be operated under vacuum, at pressures of the order of 10^{-4}Pa or lower.

However, the SEM offers several advantages over its light counterpart. These include a higher resolution, magnification, depth of field, and more versatility, as a variety of signals can be picked up (Goodhew *et al* 2003: 19).

To obtain images, the microscope uses the lenses in a demagnifying mode so that a small electron beam scans a raster on the specimen at the same time that a spot of a cathode ray tube

(CRT) is scanned across the screen (Glauert 1974: 321). Any radiation with a measurable change can be used as a signal for producing contrast in the CRT and thus, produce an image (Goodhew *et al* 2003: 125). However, the usual imaging modes are given by the signals from secondary electrons and backscattered electrons. The magnification obtained is the ratio between the distance scanned on the display (CRT) and that scanned on the specimen (Phillips 1971: 424).

3.7.2.4 X-ray dispersive spectrometry

X-ray energy-dispersive spectrometry (EDS) is a chemical analysis technique well suited to rapid qualitative analysis, covering a wide range of elements.

As explained above, x-rays are a by-product of inelastic interactions of the incoming electrons and the atoms of the sample. X-ray generation is an inefficient process compared to elastic scattering (Newbury 1986: 11). However solid state energy-dispersive spectrometers (EDS) are capable of collecting and simultaneously displaying x-ray data from a wide energy range (Williams *et al* 1986: 125). A series of characteristic peaks are obtained, resulting in plotting energy (keV) against counts.

The position of the detector relative to the sample is of high importance, and varies according to the manufacturer. The detector is enclosed in a high-vacuum tube protected from the atmosphere by an ultra-thin sheet, or "window". Certain radiation coming into the detector is limited by the collimator. For instance, the direct entry of backscattered electrons is restricted. The resolution of the detector and the beryllium window thickness require calibration. The detector itself is a piece of semiconducting silicon, whose electrons are excited generating a current proportionally related to the incoming x-ray energies. This current lasts for less than a μs and is received as a pulse and amplified. A multichannel analyser (MCA), a computer, allocates the pulse in specific channels (approximately 10000) according to different X-ray energies (Goodhew *et al* 2003: 178). Then, a histogram of energy vs. pulse counts is built. However, the resultant is not a series of lines, but of broad peaks (100 to 200 eV wide).

Quantification of the spectrum involves the removal of the background radiation (Brehmsstrahlung) and obtaining the true relative intensities of the peaks. However, interpretation is often difficult, as not only the continuum affect a given peak, but other peaks as well (Williams *et al* 1986: 124-127).

Currently, signals are processed through software packages, often calculating theoretical spectra to interpret the data that are obtained experimentally. However, in order to obtain reliable results, calibration based on standard reference materials is also necessary. Not only it must be

taken in account that each instrument introduces inaccuracies when quantifying chemical composition, but also that the standard reference materials must be varied enough to include samples of ancient material. Ideally, they should be chemically as close as possible to the sample being studied, and thus accounting for the interference that some elements may have on the measured quantities of others.

3.7.2.5 Sample preparation

Mounting

Cutting a sample by a mechanical process produces a rough and not very flat surface, which is not suitable for microscopic observation. The sample has to be ground and polished. However, to perform this processes the sample must be first set in resin.

The samples used for optical metallography under the light microscope can be used for both optical and electron microscopy. However, the sample needs to have electrical conductivity as well, in order to avoid charging on the sample surface. Insulating materials accumulate absorbed electrons until a charge build-up appears which leads to image distortion as the emission of secondary electrons is altered (ASM 1999). Since the epoxy resin the samples are set in is an electrical insulator, the samples must be coated with a very thin film of conductive material, which can be provided for metals by vapour deposition of carbon (Vander Voort 1999: 91).

Grinding

It is important to know that grinding processes will still leave some distortion in the crystalline lattice in the region close to the surface. Distortion depends on the rate of abrasion, applied load and hardness of the material. Yet, grinding with silicon carbide abrasive papers induces much less deformation than other abrasion processes such as surface grinding with alumina, or lathe turning. It is still recommendable to continue grinding for a few minutes to help to remove at least some of the abrasion damage layer left by previous grits beneath the polishing grooves; alpha brasses, which are relevant to this project (very common in Roman copper alloys of the first century AD) are especially susceptible to grinding and polishing damage (Samuels 1967: 43-95).

Polishing

After samples are ground they were subjected to polishing with diamond paste which allows for higher abrasion rates with smaller particles compared to alumina, giving a less damaging polish.

From the point of view of metallographic sample preparation, copper and its alloys are soft materials (Zipperian 2011). Standard mechanical polishing introduces deformation on the surface

that could obscure the actual structure to some degree. Plastic deformation caused by polishing, about 0.7 µm deep for 70: 30 brass using diamond paste of 1µm particle-size (Samuels 1967: 85), can affect grain orientations at the surface of the sample. However, this damage is not relevant to the present study.

Samples should be microscopically observed before etching, as sometimes as-polished surfaces are suitable to observe hard inclusions (Phillips 1971: 3) or corrosion products.

3.7.2.6 Sequence of analysis

As electron microscopy metallographic analysis and energy dispersive x-ray spectrometry (EDS) are non-destructive to the sample, these techniques can be employed before etching for optical metallographic analysis.

EDS was mainly used as a qualitative and semi-quantitative chemical analysis test, meaning that it provided a semi quantitative analysis of the elements present in the sample, and qualitative analysis for the identification of constituents, such as phases, inclusions (e.g. lead globules) or plating (such as tinning or gilding). However, EDS analysis was still able to accurately quantify the minor and major elements that constituted the objects from which samples for metallography analysis were taken.

A stable current on the sample is required for EDS analysis to produce reliable spectra of both the elemental standards used in calibration and the standards themselves. For this purpose a Faraday cup, which is a metallic enclosure used to capture charged particles under vacuum conditions, was attached to the sample holder and connected to an ammeter capable of reading current values down to $1x10^{-10}$A. Whenever EDS is used for analysis, geometry is of key importance; a flat surface, a working distance of 20mm, and tilting the sample 30° is essential for peak identification and quantification in the system used.

The Princeton Gamma-Tech (PGT) Spirit software was used to process the signals obtained by the EDS detector. First an energy calibration was performed by analyzing a pure copper standard, which is done by matching the energy (eV) readings coming from the detector with the copper peak positions from the internal library of pure elements within the software.

The next step was to create a library of spectra taken from elemental standards, which were used to calibrate the unknown sample spectra. All the standard spectra were taken under the same experimental conditions. First a spectrum from a copper standard reference material was taken at 2000 counts per second (by adjusting the current), following the manufacturer's recommendation. Without modifying the geometry of the analysis, the current in the Faraday cup was measured and

registered (1.2 nA). For all the remaining pure elemental standards, the same current value and geometric array was used to produce the spectra. This ensured that all the pure elemental standard spectra were able to be used for calibration when analysing a single sample spectrum.

Once the standard reference material spectra had been taken, unknown samples could then be run. Back-scattered electron images were used to examine the edges and bulk of the sample to identify any presence of plating, dual phases or lead globules, and images taken when found.

To collect a sample spectrum, the sample was tilted 30° and the beam focused at a working distance of 20mm. The current was adjusted so that approximately 2000 counts were registered by the software, so that all the operational conditions were similar to those present when taking the standard spectra. Three bulk spectra were obtained for each sample in total, taken on different areas of the inner surface and calibrated with the pure elemental standard spectra previously taken. A percentage for each element is independently obtained and a total is then calculated. For quantification purposes in metallic materials, deviations of no more than ±2% from 100% are accepted when obtaining the totals. Any larger deviation prompted a new analysis.

Qualitative EDS analysis was also performed to identify lead globules, tinning, and gilding on samples in conjunction with back-scattered imaging.

3.7.2.7 Standard reference materials and calibration spectra

British Non Ferrous Metals (BNF) standard reference materials, with alloy types with similar compositions to those expected for Roman alloys, were used to account for matrix effects such as overlapping or inter-elemental effects. These SRM were analysed before and after each batch of samples was analysed to check for accuracy and identify drift.

An average of the values obtained by EDS for each batch of BNF standard c42x01 can be seen in Table 3.9 together with its certified values. The relative standard deviation percentage is a measure of precision between the different batches, while the percentage error refers to the accuracy of the analysis during the run of each batch, relative to the certified values.

	%Cu	%Zn	%Sn	%Pb	%Fe
BNF certified values	**66.00**	**32.60**	**0.82**	**0.12**	**0.19**
BATCH					
Ham Hill and Cadbury Castle	**66.87**	**31.71**	**0.80**	**0.26**	**0.21**
%Error	1.32	2.74	2.65	113.77	11.03
Usk and Carlisle	**67.09**	**31.43**	**0.72**	**0.17**	**0.32**
%Error	1.65	3.60	12.11	44.44	68.07
Chester	**67.41**	**31.29**	**0.69**	**0.16**	**0.22**
%Error	2.13	4.03	15.97	29.52	14.89
Kalkriese	**67.11**	**31.34**	**0.65**	**0.22**	**0.26**
%Error	1.69	3.85	20.55	87.49	35.98
Kingsholm	**67.11**	**31.34**	**0.65**	**0.22**	**0.26**
	1.69	3.85	20.55	87.49	35.98
Precision	0.3	0.5	8.7	20.1	17.0

Table 3.9 BNF standard reference material c42x01, certified and average of obtained values for each analysis batch (EDS), the relative standard deviation of all batches and their associated error.

3.7.2.8 Limits of Detection for EDS

For this project, EDS was mainly used to quantify major and minor elements in copper alloys, namely copper, tin, zinc, copper, lead and occasionally iron. When a combination of these elements is significant enough to define an alloy type, all are above the limit of detection of this technique. The exceptions are certain brasses with very low quantities of tin, bronzes with very low contents of zinc or unleaded copper alloys. However, the limits of detection for these elements were obtained under the same experimental conditions in which the samples were analysed (Table 3.10).

The limits of detection were calculated based on analysis on the standard reference materials (see above). The calculation is based on the number of counts of a peak of the element in question and the background counts associated to it (Goodhew *et al* 2003: 200):

$$MDC = \frac{200\sqrt{\mathrm{b}}}{(\mathrm{p}-\mathrm{b})\sqrt{\mathrm{t}}}\%$$

Where *MDC* is the minimum detectable quantity, *b* is the count rate for the background, *p* is the peak count rate on the pure element standard, and *t* is the acquisition time (100 seconds).

Given the compositional range of Roman copper alloys, copper, zinc, tin, lead, and iron are the only elements that can be quantitatively analysed by EDS in this project.

Element	% Limit of Detection
Cu	0.09
Zn	0.07
Sn	0.06
Pb	0.05
As	0.13
Fe	0.09
Mn	0.09
Ni	0.09
Sb	0.09

Table 3.10 Minimum quantities detectable for EDS analysis

3.7.3 Optical metallographic analysis

3.7.3.1 Etching

After being analysed with the scanning electron microscope, the samples were re-polished to remove all traces of carbon coating before etching.

For many materials, such as copper alloys, important structural features are not revealed until an etchant is applied. Etching is considered as a controlled-corrosion process by electrolytic action. Structural variations (such as grain boundaries, grain orientation or grain internal features) define anodic and cathodic zones that provide visual contrast upon etching (Vander Voort 1999). A feature will be left in relief if it is electropositive relative to the matrix, whereas some other features will be electronegative and thus, preferentially etched (Phillips 1971: 5).

There is a great variety of etchants used in modern materials practice (ASM 1999: 827-8). However, one of the reagents recommended by Scott (2011) for ancient copper alloys is the alcoholic ferric chloride $FeCl_3$, which was used for this work.

3.7.3.2 Crystalline structure and plastic deformation

When a metal is not worked beyond an as-cast condition, the microstructure has typically the form of dendrites, arborescent structures that form when a metal is cooled slowly after being cast. This microstructure can be transformed upon re-heating the metal above a certain temperature (but below the melting point) to form a granular structure, seen as polygons in a cross section of the object. In actuality, these structures are three-dimensional crystals, or grains, whose size and degree of deformation has a direct influence on the mechanical properties of the metal.

When stress is applied to a metal beyond its elastic limit (before this the behaviour of the metal is elastic, returning to its original dimensions when the stress is removed) it undergoes plastic

or permanent deformation. The mechanism of plastic deformation is complex; resulting in slip lines, twinning, or a combination of both.

Solid state metals are crystalline structures, where the smallest units preserving the symmetry of the crystal are called unit cells. These cells are defined by linear and angular parameters which constitute crystalline systems. Most metals belong to cubic or hexagonal systems, having unit cells whose spatial repetition generates lattices: b.c.c. (body centred cubic), f.c.c. (face centred cubic), and c.p.h (close-packed hexagonal).

A series of geometrical directions and planes can be defined within the unit cell and bear a relationship to plastic deformation by the slip mechanism according to a specific crystalline system. Upon the application of stress beyond the elastic limit, part of the crystal (on most densely atom packed planes and directions according to the specific crystalline system) will displace relatively to the rest. If the load is increased, atoms on another parallel plane will move generating a step (the intersection of a slip plane with the surface of the crystal). Each elongation demands higher stress, so that the more it is worked the more difficult it is to continue elongation. This behaviour is consistent until the material fails by fracture (Avner 1974: 107).

In the case of f.c.c. metals such as copper, there are more slip systems than any other crystalline system, which macrostructurally means that for most cases a lower stress is required to attain plastic deformation.

Twinning is a movement of planes of atoms in the lattice parallel to a specific plane so that the lattice is divided into two symmetrical parts with different orientation and it involves a large number of atoms. That is, the arrangement of atoms is mirrored in either side of the common plane. However, twins can be produced by annealing most f.c.c. metals (including alloys like brass), reheating them after they have been worked. This is due to differences from the normal grain growth mechanism (Avner 1974: 116-118).

3.7.3.3 Annealing and recrystallization

Annealing is a type of heat treatment that involves reheating a metal so that it recovers its strain-free condition after being cold worked and it is accompanied by a change in the microstructure. If reheating is above a certain temperature, specific to the metal or the alloy (recrystallization temperature) new crystals are formed and are approximately uniform in their dimensions (equi-axial) with the consequent drop in the required stress for plastic deformation, allowing the metal to be further worked. Any plastic deformation on the metal below recrystallization temperature is known as cold-work.

In a micrograph, etching reveals slip lines that are seen as several closely spaced parallel lines within each grain. The orientation of slip lines between different grains can be different, as the orientation of those grains can also be different. Twinning is also visible microscopically, but its appearance differs in that it appears as broad lines or bands within the grain.

3.7.3.4 Grain size

Grain boundaries hinder slip mechanisms, which translates macroscopically in higher resistance and hardness. Since smaller sized grains mean more grain boundaries, grain size directly influences mechanical properties in metals and thus represents desirable information to have.

The shape of a three-dimensional grain is very complex, and a measure of its size is best grasped is if it is seen in a two-dimensional projection, such as a polished and etched surface. For modern metals, different methods for measuring grain size have been developed that account for relative grain size variability within a sample. The average area of a grain can be obtained with software capable of identifying grain boundaries. Other practical, non computer-based methods are, however, still widely used, such as the linear-intercept method adopted here.

In the linear-intercept method, a line of known length is laid on a micrograph and the number of intersections with grain boundaries is counted. The process is repeated for several random line orientations so that a relative size of the grains is obtained after averaging the number of intersections per unit of length for each of the randomly oriented line segments (ASTM E112-10 2012)

For samples with heavily deformed grains, so that they are deformed along certain direction, the circular intercept method is more suitable. In this method, a template with concentric circles of known circumference is placed on the image and the number of grain boundary intersects is counted for each circle.

These methods were developed to measure grain size in modern metals and alloys, which generally show a higher regularity in their microstructure, including grain size. However these methods are used in archaeometallurgical studies (Scott 1991; 2011).

3.7.3.5 The statistical treatment of metallographic data

From the total number of samples, approximately 30% was analysed metallographically. A table was created for all the samples considering attributes suitable for metallographic analysis:

- Type of microstructure (dendritic, granular)
- Presence or absence or plating

- Type of plating (silvering, tinning)
- Grain size (mean intercept, ASM number)
- Presence or absence of twinning
- Degree of presence of strain lines
- Degree of deformation
- Lead globules presence
- Number of phases present

The frequency of strain lines and the degree of deformation were treated as ordinal variables by associating a number to them. They were not considered interval variables, as it is not possible to interpret the distances between the numbers assigned to them.

In the case of strain lines, qualitative observations were transformed into numeric values, as it is shown in Table 3.11.

Strain Lines	**Value**
Absent	1
Scarce	2
Localised	3
Generalised	4
Abundant	5

Table 3.11 Strain lines, assigned values for analysis.

The degree of deformation variables were also coded into numeric values (Table 3.12).

Degree of Deformation	**Value**
As cast	1
Slight	2
Moderate	3
Moderate – Heavy	4
Heavy	5
Extremely Heavy	6

Table 3.12 Degree of deformation, assigned values for analysis.

The ‘absence’ or ‘presence’ values were assigned numbers ‘1’ and ‘2’, respectively, as corresponding with dichotomous nominal variables (Fletcher & Lock 1991).

While the use of mean intercept or average diameter gives a more accurate value than the ASM number, the latter is a better grouping variable. For these reasons both were chosen to be present for the analysis.

3.7.4 Statistical analysis for AAS data (a brief explanation of the techniques)

In certain types of data, multiple variables measured on each of a set of sampling units are correlated. Multivariate analyses aim to identify the structure in these data by simplifying correlations, reducing the set of dimensions (Rencher 2002). Multivariate analysis, such as discriminant analysis (DA) and principal component analysis (PCA), has been used in the past on trace element compositional data, as a means for essaying provenance attribution for ceramics, metals or flint, back to their original mineral sources, with some success, especially with the analyses of rocks (Craddock *et al* 1983; Baxter 2008). However, for this thesis, provenance analysis to a mineral source was not intended, but rather connection to a particular workshop or metallurgical tradition associated with a military unit.

A set of variables (chemical elements) were measured for each sample of each object with atomic absorption spectrometry. Multivariate analysis was needed to identify potential multi-dimensional correlations between measured values across all the objects, and was considered as an exploratory technique for this project. Leese (1981) reviewed the use of a variety of statistical methods for examining analytical data. She argued that 'hypothesis testing' methods (such as discriminant analysis) where data was partitioned along archaeological criteria (typology, provenance, chronology) were preferable to 'pattern searching' methods (such as cluster analysis).

Here two approaches can be followed. The first one involves assuming that there are a definite number of military units, e.g. two, *legio II,* and *legio XX*. Multivariate analysis can then help to obtain a probability of ‘membership’ for each sampling unit to each group. A technique called discriminant analysis can be of use in this case. The second approach does not assume the existence of particular groups prior to multivariate analysis and aims to identify groups within the data. A technique that exemplifies this case is principal component analysis (PCA).

Raw data from atomic absorption spectrometry consist of a set of chemical elements measured for each object sample, which due to the nature of analytical techniques do not sum up to 100%, in which the data are called sub-compositional. To obtain a fully compositional set of data,

normalization can be performed, so that the sum of element measurements for each object sample is 100% (Baxter & Freestone 2006). However, certain transformations have to be done before the data can be analysed by multivariate techniques, since these methods assume that the data is close to being normally distributed.

3.7.4.1 Data processing for statistical analysis

Compositional data in which some elements are present below the limit of detection, known as censored data, are common in archaeometric studies, and need to be addressed before statistical analysis takes place. Values below limit of detection can be (Baxter 2003):

- set as zero, which is not recommended if the data set is to be logarithmically transformed afterwards,
- estimated by maximum likelihood, which defeats any purpose for a following grouping analysis, or
- substituted (the most commonly used strategy), where censored values are replaced by αLOD where $0<\alpha<1$. The limit of detection can be replaced thus, by the minimum available measurement for a variable, which is normally taken at 0.5 or 0.55 LOD, provided the number of censored observation is less than 10% of the total (Baxter 2003).

In this thesis substitution by 0.5 LOD was used for values below limit of detection. For major and minor elements, or for the elements which define alloy type in Roman metallurgy, such as copper, zinc, tin and lead this is not a problem. However, in the case of traces this can introduce artificial structure in the data, which may cause the removal of a variable (chemical element) from the analysis if there are many censored data associated with it.

3.7.4.2 Univariate and bivariate plots

The samples were first analysed on a site-by-site basis by generating univariate and bivariate plots for each element, to avoid data from other sites that might obscure distribution patterns or possible correlations. Histograms inform about how the composition of each element is distributed in the artefacts of each site, while bivariate plots can sometimes show correlations between two variables.

Certain elements in copper alloys are usually regarded as geo-chemically related and correlations can be found between them. In the case of the copper alloys in this project, these

elements are silver, arsenic, cobalt, nickel and antimony (Tylecote *et al* 1977; Ponting 2006; Hauptman 2007). Other elements are related to the technology employed in manufacture. A substantial amount of the objects analysed in this thesis are made of brass. However, significant levels of manganese are not associated with the copper, but are transferred from the zinc ore (smithsonite) during the cementation process (see Section 2.9.3.2). This was explored by zinc and manganese bi-plots.

Once each site was individually analysed, data from different sites was plotted simultaneously for various sites. However, to account for higher order correlations amongst the elements, multivariate analysis is needed. Principal component analysis (PCA) and discriminant analysis (DA) are two common independent ways to look for such correlations.

3.7.4.3 Data transformation for multivariate analysis

Compositional data cannot be assumed to be normally distributed. Most multivariate analysis methods assume normality in the data and tend to impose a normal structure on the groups found, which can be misleading. There are methods that transform the data to normality (like 'dilution' correction methods), or log transformations can be used instead (Baxter 2001).

AAS analysis also produces a set of data in which the sum of chemical elements for each object sample does not equal exactly 100%. To apply any of the data transformations mentioned above the data for multivariate methods such as principal component analysis (PCA), the data were transformed to a fully compositional set by normalising them so that the sum of the variables (chemical elements measured) of each case (object sample) summed 100%.

Fully compositional data of certain archaeological materials such as glasses or metals still present an additional situation that has to be addressed if the elements present at trace levels are of concern. The 100% sum constraint together with the fact that normally two or three chemical elements account for more than 95% of the total (as in the case of copper alloys) pose a problem, known as the 'closure problem', to clustering techniques such as principal component analysis, by negatively biasing existent correlations within the data (Baxter 1992). This is due to clustering analysis being very sensitive to scale, in the case of copper alloys this being the huge difference of presence of certain chemical elements, such as copper, tin, zinc and lead, when compared to trace elements. Baxter (1992) proposed a separate analysis of two subsets of the compositional data, one containing major and minor/elements (those above 1.5 – 2%), and the second containing the transformed data of trace elements. Even when separating the major and minor elements from the

analysis of trace elements, closure with always influence the data to some point (Filzmoser *et al* 2009), a problem that can be minimized by transforming the data.

There has been a long debate of whether a data set has to be transformed and how, and if it is transformed, the data has to be standardised afterwards. It seems that there are not generalised guidelines as to which data transformation to employ (Baxter 2008). Logarithmic transformation is frequently used, as it tends to stabilize the variance of the variables so that they have approximately equal weight in an unstandardised principal component analysis (Baxter 1995). However, Aitchison *et al* (2002) argue against logging the dataset omitting dominant variables (arguing that information provided by compositional data is relative, as opposed to absolute values of the components of compositions) and suggest the use of logarithms of ratios for all the compositional data. Baxter (2008) argues that similar results to log ratios are obtained with analyses done with logarithmic transformations of sub-compositional data of trace-elements. This is to extract subsets of the data (trace elements) but re-scaling them to 100%. For multivariate analysis of the data used in this thesis, trace element values were re-scaled to the copper, and then transformed via natural logarithms.

An additional issue is that antimony can be related to lead (Tylecote 1986: 78). In order to deal with this potential problem, before scaling to the copper antimony was plotted against lead to identify any clear correlation; none were found (see Chapter 5).

3.7.4.4 Principal component analysis (PCA)

Principal component analysis is a statistical method used to identify or display structure within variables from a data set, such as chemical composition of archaeological artefacts, and involves the linear transformation of correlated variables to uncorrelated variables, or components (Baxter 1995) that work as independent aggregates of the original variables. In the case of compositional analysis, each of the chemical elements measured in a sample would constitute a variable. The information obtained can be used not only to study the relationship between different cases (samples), but also between variables or between cases and variables. PCA can be very useful when the original multivariate data do not conform to a normal distribution (Baxter 2003: 74).

For PCA analysis involving chemical composition of a sample of artefacts, as in the case of this project, transforming the data by taking logarithms before PCA is useful, since logged data then will have a similar order of magnitude with comparable variances (Baxter 2003). PCA analysis of

archaeometric data transformed in different ways, such as standardised and non-standardized logged data produce results that often have similar interpretations (Baxter 1995).

A linear combination is extracted from the data by multiplying a matrix (the original data) by a specific vector (called an eigenvector) so that the data are transformed in a particular way. Geometrically this represents the data being projected onto a new axis (or dimension, or component). Mathematically, the length of the new axis (formed by the sum of the squared loadings, or correlations between the original variables and the newly created component) is the eigenvalue. An eigenvalue of 3, for example, would mean that the component produced accounts for three times as much variance as any original variable. If ten original variables had been considered in the analysis, 3/10, or 0.3, means that this particular component would account for 30% of the total variance.

The second linear combination would be on an axis perpendicular to the first linear combination, and generated by multiplying another eigenvector by the data matrix, which means these combinations are independent from each other. The same applies for the following components, so that all the linear combinations produced are orthogonal, and thus, uncorrelated with each other.

The components are hierarchically generated and numbered depending on the proportion of the variance of the data they explain. The first component accounts for the highest variance percentage, followed by the second, and so on. The goal is to explain as much variance as possible with the fewest number of components. Though typically 2 or 3 components are used to explain most of the variance observed in the data (so that they can be plotted, thus aiding visual identification of groups), there are mathematical and graphical criteria that suggest a statistically meaningful number of components. However, selecting the number of groups is done usually as a rule of thumb, with number of components necessary to explain 70% to 80% of the data being considered as enough to summarise the behaviour of the original dataset (Baxter 2003: 80).

A full components solution would have as many linear components as original variables were, but this would defeat the purpose of the analysis, which is reducing dimension so that a more manageable size of variables is obtained, which can still explain most of the variance within the data (a truncated components solution).

After the components are obtained, their scores can be arranged into bivariate plots (each score being labelled as a case), or the coefficients of each components can be plotted against each

other, which would give information about how variables (chemical elements in this case) are correlated with each other for the pair of components plotted.

Principal component analysis is very sensitive to discontinuities in the data, such as missing values, or to outliers, which have to be removed.

3.7.4.5 Discriminant analysis (DA)

In discriminant analysis, a grouping variable is employed to predict group membership from a set of predictor variables using a criterion variable, each case assumed to be a member of only one group. DA can also be used in conjunction with other multivariate methods to identify cases that sometimes are wrongly assigned to belong to certain groups (after performing clustering analysis, for example).

In archaeology Fisher-Rao linear discriminant analysis (LDA) is the method most commonly used, while some others such as quadratic discriminant analysis (QLDA) are less widely used. In Fisher's LDA the probability of group membership is the same for any of the groups, and the goal is, geometrically, to assign a case to the group with the nearest centroid, as measured by Mahalanobis distance (Baxter 2003: 107). Distances in archaeology serve the purpose of allocating isolated cases to one of several predefined groups based on the distance from the case to the group (Baxter 2003: 70). The Mahalanobis distance is measured between the means of the two groups that constitute the data matrix and results from maximizing the Euclidean distance (simple point to point distance) between the groups. Since the Mahalanobis distance carries an estimate of the covariance matrices of the two groups, this meaning that it allows for the variables to be correlated, unlike the Euclidean distance. Geometrically, this means that the Mahalanobis distance, unlike the Euclidean distance, allows for variance to change along different dimensions.

For this project the predictor variables are the chemical elements measured and the predictor variable (which is categorical) would be the workshops or military unites, e.g. *Legio II* or *XX*, derived from the archaeological information for each site.

The success of a classification rule generated by DA can be measured by estimating the error rate by re-substitution, or applying the classification rule to all the original data set. A second way (cross validation) to evaluate the classification rule is to apply it to randomly divided subsets of the data and taking an average of the error rate across the analysis of those subsets. A form of cross validation widely used in archaeology is the 'leave-one-out' approach (LOO), in which the classification ruled is tried on each individual case at a time (Baxter 2003: 108-9).

Although LDA performs optimally when the variables have a normal distribution, the solutions are still valid whether there is normality in the data or not. If LDA is used mainly to show group separation graphically, the data do not need to be normally distributed (Baxter 2003: 107).

3.8: Conclusion

This chapter described the process of selection of the assemblages for analysis (South Cadbury, Ham Hill, Usk, Kingsholm, Chester, Carlisle and Kalkriese), the different techniques of analysis and data processing employed in this thesis, and technical considerations and assumptions followed during the analysis. The next chapter presents the assemblages and their associated sites.

Chapter 4: The assemblages of objects analysed.

This chapter presents the objects sampled for analysis and the sites from which they originate, based on the selection criteria and methodology of analysis detailed in Chapter 3. The chapter is divided into sections defined by the different sites from which the samples analysed were obtained. The assemblages are presented in a sequential manner, beginning with a summary description of the site and its excavation, followed by particular characteristics of the site or the assemblage in general. Whenever there has been metallurgical analysis performed on objects coming from the same site from which the samples for analysis were taken, it is noted. An overview of the sampled objects is then given, mentioning object type and approximate dating.

A table with information on each sample is found at the end of the chapter. Each sample was named based on its small find number, but preceded by letters related to the site name of the museum (Table 4.1). The same system is used elsewhere in this work. Information on the type of object is then shown in the following column of the table where details about the context are also provided if it is known. Objects from some sites (Carlisle, Usk and Chester) date from different periods, in which case this is indicated in the table. Another column contains information about where the objects appear in published sources (the objects from Kingsholm, Chester, and some from Ham Hill and Kalkriese have not yet been published). The last column contains photographs of the objects sampled.

Sample code	Site
CC	Cadbury Castle
HamH	Ham Hill
CSL	Carlisle
USK	Usk
CHE	Chester
GLC	Kingsholm
K	Kalkriese

Table 4.1 Codes used to name each sample

Since documentary and epigraphic sources point to an association between the sites discussed in this chapter and certain military units (the legions *II Augusta, XX Valeria Victrix* and *XVII-*

XIX), a brief account of their probable location can be found at the end of this chapter. Discriminant analysis (see Section 3.7.4.3.3) requires *a priori* group attribution for the method to work, and the information on the military units mentioned above served for this purpose (see Chapter 5).

4.1 South Cadbury Castle

(South) Cadbury Castle is a hill fort on top of a steep-sided hill in south Somerset that has been occupied continuously from the early Neolithic through to the Saxon period, with Iron Age and Roman occupation being the most intensive. During the late Bronze Age and the early Iron Age the site changed from an open settlement to a hill fort (Barrett *et al* 2000a: 5).

The violent capture of the fort by the Romans and the associated massacre is thought to have taken place c.AD45 and has been related to events at Maiden Castle and Hod Hill, as Vespasian campaigned across southern Britain (Woodward 2000: 106). This interpretation has since been contested, where it is thought that the event was connected with the aftermath of the Boudiccan Revolt of AD60/61 (Manning 2002: 34).

The fort was subsequently occupied by the Romans with two important periods of activity; the first dating to the mid- to late first century, and a second period in the fourth century relating to the construction of a temple (Barrett *et al* 2000b: 169). The military metalwork belongs to the first period (Bishop 2000: 242).

The Military Equipment

The first systematic excavation of the hilltop was conducted by St George Gray in medieval ploughing at the site. The recovery of objects, including military equipment, had been reported already in the 18th century (Freeman 2000: 7). The 8 copper-alloy military equipment objects from Cadbury analysed here were found during the 1966-1970 excavations at Cadbury Castle conducted by Leslie Alcock (Alcock 1970). The metalwork found in the 'massacre' deposit contexts (in the south-west gate) includes both native and Roman military equipment, and seems to be associated with a battle and a subsequent massacre. The Roman equipment is dominated by spearheads and bolts, but includes *lorica segmentata* fittings (Woodward & Hill 2000).

Most of the military equipment, however, was found in the areas corresponding to the barracks of the fort (in the so-called Plateau sites). It is typical of the second half of the first century, and consists mainly of copper-alloy objects: *lorica segmentata* and helmet fittings, sheet binding, and cavalry harness implements (Bishop 2000: 242). Of the sampled objects, only CC145 (see Table 4.2) was found in the 'massacre' contexts. Even if the sample size is small for this site, the type of

objects is representative of the site (Table 4.2), and comprises *lorica segmentata* fittings, a fragment of shield binding, and a fragment from a plated dagger plate.

All the objects from Cadbury sampled for this project are held in the Museum of Somerset, in Taunton.

Previous copper-alloy analysis

Northover (2000) analysed copper-alloy metalwork of different periods from Cadbury Castle, including Iron Age and Roman objects. The Iron Age objects included U-shaped bindings and metalwork waste, whereas the analysed Roman objects were mainly brooches, but also some decorative elements. This analysis measured 13 elements down to trace levels using electron probe microanalysis with wavelength dispersive spectrometry, with the Iron Age material having characteristic impurity patterns for south-central and south-western England (with iron, arsenic, nickel and cobalt as main impurities, cobalt being greater than nickel).

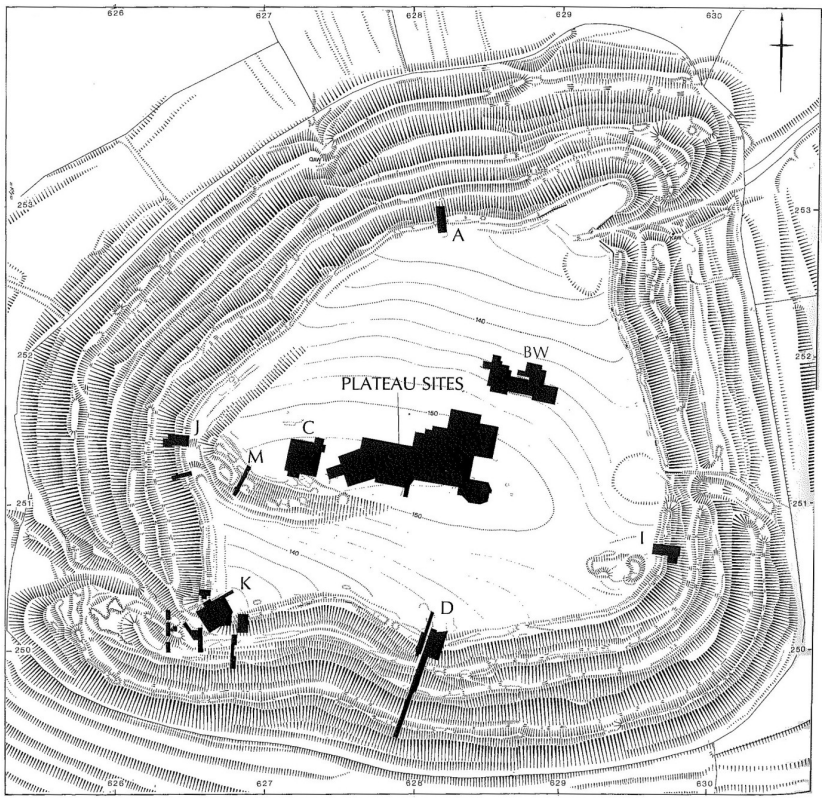


Figure 4.1 Cadbury Castle. Excavated sites, with the 'Plateau' sites and the 'Massacre' in Site K (from Barrett *et al* 2000a)

Sample	Description	Context	Reference	Photograph
CC113	Shield binding	Barracks	Barrett *et al* 2000, fig. 120, no.1	
CC136	*Lorica segmentata* lobate hinge	Barracks	Barrett *et al* 2000, fig. 121, no.24	
CC145	*Lorica segmentata* decorated roundel, plated	South-west entrance (Massacre deposit)	Barrett *et al* 2000, fig. 122, no.33	
CC147	*Lorica segmentata* decorated roundel, plated	Barracks	Barrett *et al* 2000, fig. 122, no. 35	

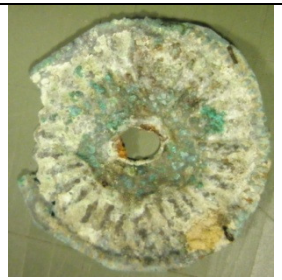
CC148	*Lorica segmentata* decorated roundel, unfinished	Barracks	Barrett *et al* 2000, fig. 122, no. 36	
CC153	*Lorica segmentata* decorated roundel	Barracks	Barrett *et al* 2000, fig. 122, no. 41	
CC156	Belt dagger frog fragment, plated	Barracks	Barrett *et al* 2000, fig. 123, no.45	
CC164	Horse harness 3-way strap junction, plated	Barracks	Barrett *et al* 2000, fig. 123, no.53	

Table 4.2 Sampled objects from South Cadbury Castle.

4.2 Ham Hill

Ham Hill is the site of an 88.1ha hill fort surrounded by two ramparts and ditches. It is a rectangular shaped plateau with a prominence at its north-west corner, the spur (Sharples & Evans 2010: 2). There is evidence of occupation at the site from Mesolithic times (Brittain 2013: 15).

Roman military occupation of the site seems to be confined to the middle of the first century AD, during the time of the conquest of the south-west by Vespasian and *legio II Augusta*, but there is evidence of later Romano-British presence (Gray 1924: 106).

Excavation at Ham Hill

Since Roman times the site has been extensively damaged by quarrying and ploughing (notably in its eastern half). Many of the objects collected from Ham Hill in the second half of the 19th century were found as a result of quarrying operations in the area, and so their context is lost (Gray 1910: 50). The 37 scale *lorica squamata* parts, for example, were found in 1885. It was not until 1907 that archaeological excavations began, south of the amphitheatre, at Site A'07, where a Romano-British dwelling with a workshop was excavated and objects from the first centuries AD were found (Walter 1907). In the same year objects of the 2nd and 3rd centuries were found at Site B'07. In 1923 some cuttings were excavated in the base of the northern slope of the hill (Gray 1924; 1926) and equipment found (see HamH1324 in Table 4.3).

From 1983, excavations were conducted in the south-west corner of the fort (Smith 1991; McKinley 1999; Leivers *et al* 2006). The south of the fort is currently being excavated (Slater & Brittain 2012; Brittain 2013).

Sampled objects

Twenty-three objects from Ham Hill were sampled for this thesis (See Table 4.3). The equipment analysed comprises horse harness equipment (9 objects), shield binding (3), and fittings from aprons (3), studs (2), *lorica segmentata* (1), and belts (1). Additionally, a tinned *lorica squamata* scale was sampled and analysed by EDS and metallographically (but not by AAS).

All the sampled objects belong to the collection of the Museum of Somerset in Taunton.

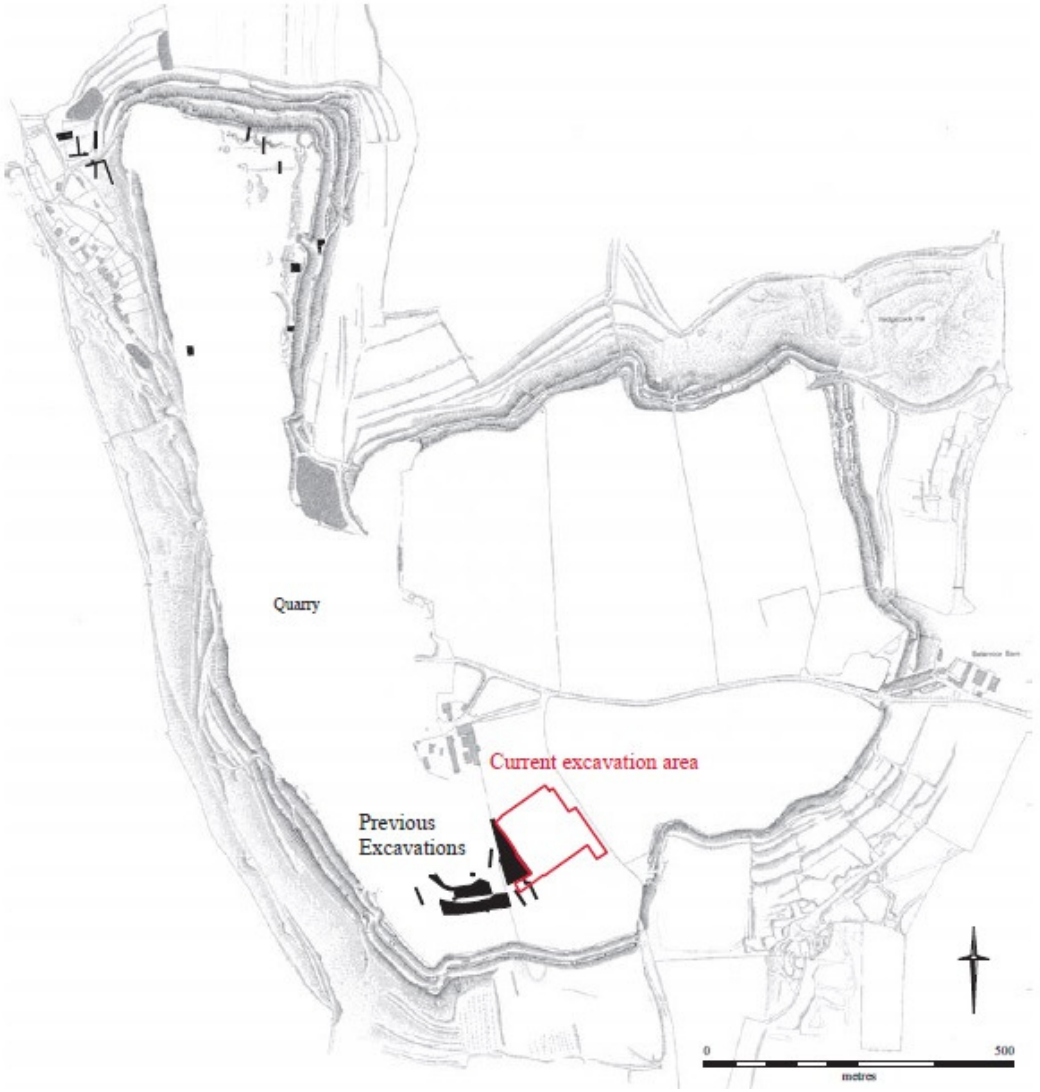


Figure 4.2 Ham Hill, the fort and excavated sites (from Brittain 2013: Fig.1).

Sample	Description	Reference	Photograph
HamH1282_7	Apron pendant	Unpublished	
HamH_1290	Horse harness strap end fitting, (Bishop Type 6a), plated	Unpublished	
HamH1291	Belt plate with part of hinge	Unpublished	

HamH1292	Apron terminal, plated and inlaid	Unpublished	
HamH1324	Horse harness pendant, (Bishop Type 8g)	Gray 1924, Pl. XIII, E15	
HamH1912_75	Stud	Unpublished	

HamH1994_8	Shield binding	Unpublished	H 
HamH491994_34	Horse harness junction loop	Unpublished	
HamH62_A_17	Horse harness junction loop	Unpublished	
HamHA1193	Belt buckle, plated	Unpublished	

HamHA1286	Mount	Unpublished	
HamHA1288	Apron plate	Unpublished	
HamHA1314	Horse harness circular boss	Unpublished	
HamHA1323a	Horse harness female strap junction	Unpublished	
HamHA1323b	Horse harness strap hook	Unpublished	

HamHA1326	Female strap fastener, (Bishop Type 1a)	Unpublished	
HamHB07	Stud	Unpublished	
HamHE12	Shield binding	Unpublished	
HamHE15	Horse harness pendant, (Bishop Type 8g)	Unpublished	

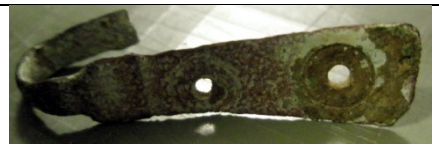
HamHE16	*Lorica segmentata* tie loop	Unpublished	
HamHE21	Horse harness strap terminal, (Bishop Type 5), plated	Gray 1926, Pl. XIV, E21	
HamHE33	Shield binding	Unpublished	
HamHF_11_1912_76	Stud	Unpublished	

Table 4.3 Sampled objects from Ham Hill

4.3 Carlisle

Carlisle is located at the west end of the Stanegate in northern England, a strategic road that linked the site with other Flavian forts to the east, including Vindolanda and Corbridge (Breeze & Dobson 2000: 17).

Based on pottery sequences, there were several phases to the occupation of Roman Carlisle (Howard-Davis 2009; Swan *et al* 2009). Construction and occupation of the first turf-and-timber fort took place between AD72-3 and 83-4, followed by refurbishment probably because of the arrival of new troops between 83-4 and 93-4. This fort was demolished between 103 and 105. A second fort was built during the following 20 years. This fort probably had a more industrial function from 125 to the 140s, as it supported the construction of Hadrian's Wall. The second fort was demolished in the mid-second century and then abandoned or at least its occupation significantly decreased. The fort was rebuilt in stone in the early third century and underwent several alterations over the course of the following two centuries, until it was demolished in the early fifth century.

The units in garrison

The garrison stationed at Carlisle seem to have been a combination of legionary and auxiliary forces. Legionary troops were probably presents as detachments in association with building operations in the fort (Howard-Davis 2009).

The presence of two men from *legio XX* is attested by a stylus tablet found in a context of AD83-4. This suggests the presence of detachments from that legion (Swan *et al* 2009). Tiles stamped by *legio IX* and *XX* have been found at Scalesceugh. This was a kiln site 9km south-west of Carlisle, and was active during the first and second centuries AD (Swan *et al* 2009: 590). Additionally, a loan agreement made by two soldiers of the *legio XX* was found amongst writing-tablets from Carlisle (McCarthy *et al* 1982; Bidwell 2007).

It is known that *legiones VI* and *XX* were involved in the construction of Hadrian's Wall (Breeze & Dobson 2000: 66). Swan *et al* (2009) associated some Hadrianic finewares found in Carlisle with the two legions (Ebor wares associated with the *VI* and Wilderspool wares with the *XX*). At this time Dorset BB1 pottery arrived in the area, and it has been associated with *legio II Augusta*, which as noted was involved in the construction of the Wall.

The reconstruction of the fort in stone could have been aided by *legio VI Victrix*, to which a stone found in the east wall of the *principia* hints but, if so, then the legion's stay was temporary. However, epigraphic evidence suggests that detachments of legions *II Augusta* and *XX Valeria Victrix* were present at the site (Howard-Davis 2009). The same three legions are represented by stamped

tiles (Pringle 2009), the most frequently represented being of *legio XX*, followed by *legio II.* The tiles possibly date from the early second century. A cavalry unit stationed in Carlisle in the late 1st century could have been the *ala Gallorum Sebosiana* (Howard-Davis 2009), but if so it was moved in the early second century to Lancaster (Shotter 2009). The mounted troops from the second fort could have been the *ala Petriana* (Breeze 2006).

Metal finds

The metal objects are very well-preserved due to the waterlogged conditions in which they were found. This has caused many artefacts to keep their original colours and patterns (Bishop & Howard-Davis 2009: 687). A significant amount of the copper-alloy scrap from military objects came from a building very close to the *principia* of the second fort, and appears to have been a repair shop or a workshop manufacturing simple objects (Howard-Davis 2009: 515). The objects found here represent a transition to the Antonine period, when military equipment significantly changed. As such, there are objects from both periods represented (Bishop 2009).

For the purposes for this thesis, objects from the most important periods in terms of military equipment were chosen. Of the 22 sampled objects, 8 belong to the second half of the 1st century AD, and 12 correspond to the first half of the same century. The remaining two are late second or third century objects. From the total 22 objects, 10 belong to horse harness equipment, and the rest are body armour, both *lorica squamata* (5) and *segmentata* (3), helmet fittings (3), and belt fittings (1). All the sampled objects are stored in the Tullie House Museum in Carlisle and are the results of the 1998-2001 excavations (Howard-Davis 2009).

Sample	Description	Context	Period (by Context)	Dating	Reference	Photograph
CSL 2042	End of strap junction	*3954* Floor, Building 4653	AD72-3 to 83-4	2nd half 1st century AD	Howard-Davis 2009, Vol. 3 No 275	
CSL 2043	Strap junction	*3632* Fill of construction trench	AD83-4 – 93-4.	Late 1st century	Howard-Davis 2009, Vol. 3 No 231	
CSL 2788	Pendant, Bishop (1988) Type 11	*4505* Fill of drain	AD93-4 to 103-5	Late 1st century	Howard-Davis 2009, Vol. 3 No 346	

CSL 3435	*Lorica squamata*	*6679* External deposit	AD105 to 125	Early 2nd century	Howard-Davis 2009, Vol. 3 No 702	
CSL 3897	Strap end	*5561* Road surface	3rd to 4th century	Mid 2nd century	Howard-Davis 2009, Vol. 3 No 492	
CSL 3909	*Lorica squamata*	*6013* Fill of stakehole	2nd to 3rd century	2nd to 3rd century	Howard-Davis 2009, Vol. 3 No 534	
CSL 3946	*Lorica squamata*	*6182* Make-up deposit?	AD140s	Mid 2nd century	Howard-Davis 2009, Vol. 3 No 547	

CSL 3962	Strap junction, spectacle type	*6526* External deposit	AD105 to 125	Early 2nd century	Howard-Davis 2009, Vol. 3 No 659	
CSL 3985	Strap junction	*6588* Occupation deposit	AD125 to 140s	Mid 2nd century	Howard-Davis 2009, Vol. 3 No 666	
CSL 4052	Strap junction, unusual	*7537* Fill of drain	AD 72-3 to 83-4	2nd half 1st century AD	Howard-Davis 2009, Vol. 3 No 1064	
CSL 4380	Ear or cheek-piece fragment	*7152* Cut of construction trench	AD105 to 125	Early 2nd century	Howard-Davis 2009, Vol. 3 No 811	

CSL 4384	*Lorica segmentata* hinge	*4101* Cut of drain robber trench	AD72-3 to 83-4	2nd half 1st century AD	Howard-Davis 2009, Vol. 3 No 308	
CSL 4387	*Lorica squamata*	*7336* Fill of ditch	AD103-5	Early 2nd century	Howard-Davis 2009, Vol. 3 No 876	
CSL 4409	*Lorica segmentata* hook	*6956* Fill of construction trench	AD105 to 125	Early 2nd century	Howard-Davis 2009, Vol. 3 No 784	
CSL 4413	Ear protector	*6872* Stake	AD105 to 125	Early 2nd century	Howard-Davis 2009, Vol. 3 No 752	

CSL 4414	*Lorica segmentata* hinge fragment	*6645* External deposit	AD72-73 to 83-84	2nd half 1st century AD	Howard-Davis 2009, Vol. 3 No 682	
CSL 4450	*Lorica squamata*	*7542* Fill of construction trench	AD72-3 to 83-4	2nd half 1st century AD	Howard-Davis 2009, Vol. 3 No 1118	
CSL 4772	Saddle plate, Bishop (1988) Type 6	*3426* Cut of gully	AD103-106; Demolition of the first fort	Early 2nd century	Howard-Davis 2009, Vol. 3 No 217	
CSL 4781	Horse harness strap mount, Bishop Type 6j	*3572* Fill of linear feature	AD105-25	Early 2nd century AD	Howard-Davis 2009, Vol. 3 No 228	

CSL 4788	Cheek-piece binding	*3777* Fill of roadside channel	AD83-4 – 93-4	Late 1st century	Howard-Davis 2009, Vol. 3 No 240	
CSL 6043	Pendant	*6324* Make-up deposit	AD125 to 140	Mid 2nd century	Howard-Davis 2009, Vol. 3 No 588	
CSL 6224	Buckle plate	*5259* Fill of post pipe	Late Roman	Second century or later	Howard-Davis 2009, Vol. 3 No 409	

Table 4.4 Sampled objects from Carlisle

4.4 Usk

Usk was the site of a pre-Flavian legionary fortress in south Wales, which was followed by a Flavian period fort, and later by a settlement from the second to the fourth centuries (Marvell & Maynard 1998). It was built in c.AD55, and was the base of *legio XX* until 66. Military occupation continued in the Flavian fort, and an auxiliary unit, the *cohors II Varcianorum Equitata*, seems to have been the garrison between 90 and 120 (Marvell *et al* 1996).

Excavations between 1965 and 1976 concentrated in the area of the legionary fortress (c. 55-60), moving to immediately south of the fortress in 1994 (Marvell & Maynard 1998), and the Flavian fort between 1986 and 1988 (Marvell *et al* 1996).

Most of the military equipment found was probably deposited as the pre-Flavian fortress closed. It could be considered scrap material that was finally discarded after waiting to be re-used. After the closure of the fortress, the construction of the Flavian fort cut into the pre-Flavian context. This caused some objects from the fortress period to be found in later contexts (Manning *et al* 1995).

The objects from Usk used in this study were found during excavations that took place between 1965 and 1976. The Roman *militaria* consisted of belt buckles and fittings, dagger scabbards and fittings, projectiles, *lorica* fittings and horse harness equipment. Not only are the three usual *lorica* types (*segmentata*, *squamata*, and *hamata*) represented, but also fragments of *lorica plumata*, a rare type of armour consisting of scales attached to chain-mail armour (Manning 1995).

The artefacts are stored in the National Roman Legion Museum, located in Caerleon and were published by Manning *et al* (1995). The initial plan was to obtain a sample closer in size to be representative of the assemblage, but only 7 objects of the 25 requested initially were approved for sampling. All except one of the sampled objects, which comes from a third century context (a scabbard slide), are pre-Flavian in origin and consist of 2 *lorica segmentata* fittings, 2 horse harness fittings and 2 belt buckle fragments.

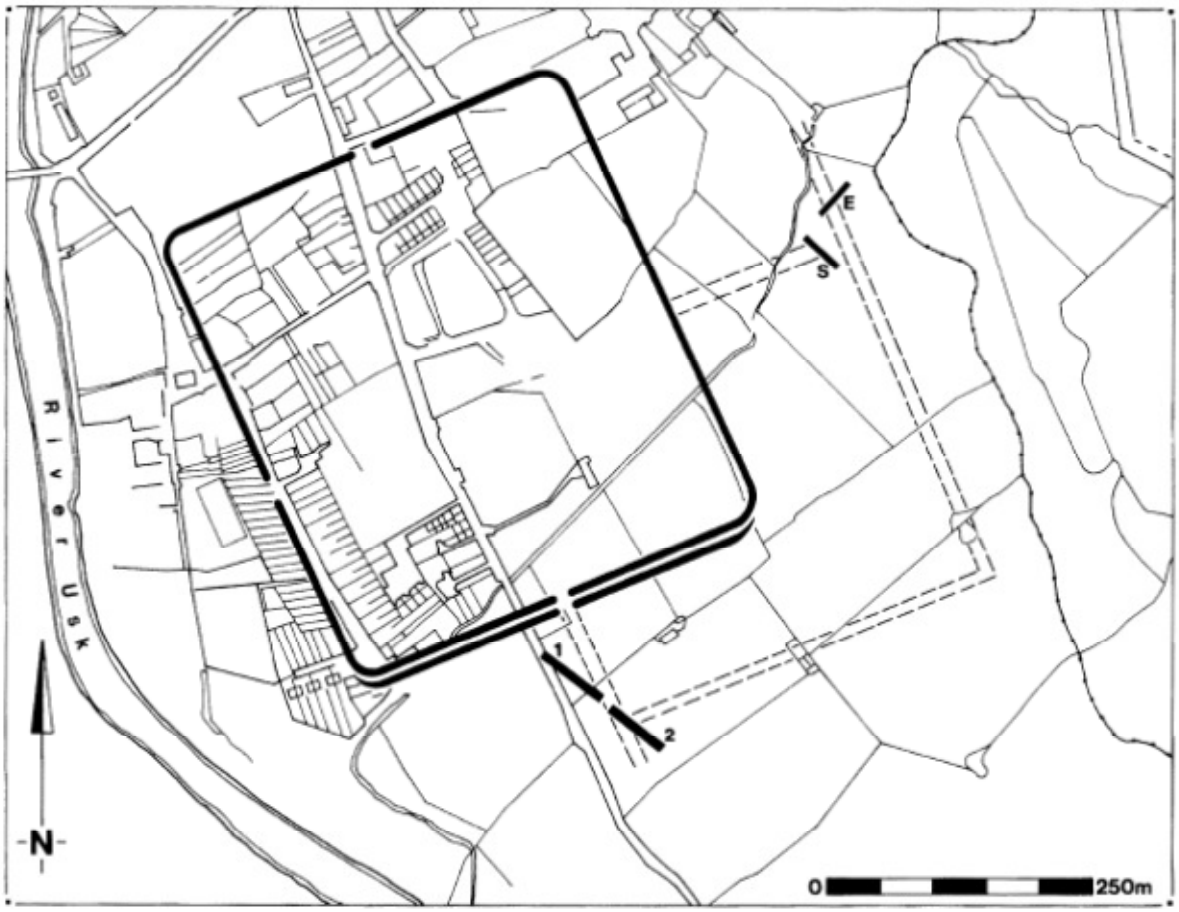
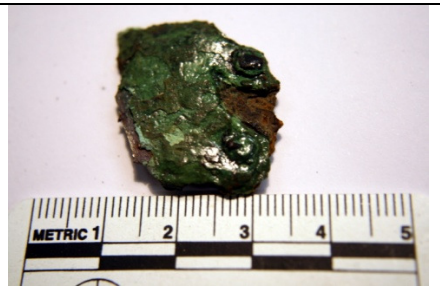


Figure 4.3 Usk: The pre-Flavian fortress, (from Marvell & Maynard 1998).

Sample	Description	Context	Dating	Reference	Photograph
Usk ManFig5No36	Belt buckle	Fortress pit, pre-Flavian	Pre-Flavian	Manning *et al* 1995, fig.5, no. 36)	
USK ManFig3No7	*Lorica segmentata* lobate hinge	Pre-Flavian fortress latrine	Pre-Flavian	Manning *et al* 1995, fig.3, no. 7)	
USK ManFig4No8	*Lorica segmentata* hinged buckle	Third century well	Pre-Flavian	Manning *et al* 1995, fig.4, no. 8)	

USK ManFig8No6	Scabbard slide	Third century pit	Third century	Manning *et al* 1995, fig.8, no. 6)	
USK ManPag40No8	Harness ring	Pre-Flavian fortress ditch	Pre-Flavian	Manning *et al* 1995, p.40, no. 8)	
USK ManP18No35	Buckle tongue	Pre-Flavian fortress pit	Pre-Flavian	Manning *et al* 1995, p.18, no. 35)	
USK Man Pag40No3	Junction loop, (Bishop's Type 1d)	Third century pit	1st century AD	Manning *et al* 1995, p.40, no. 3)	

Table 4.5 Sampled objects from Usk

4.5 Chester

It seems that there was Roman military activity in Chester in the late 40s and certainly by the year 60. The Roman fortress was then laid-out (c.AD74) and built in the late 70s (Mason 2000). *Legio II Adiutrix,* after participating in the suppression of the Batavian Revolt was taken to Britain by Cerialis (Pollard & Berry 2012). After a stay at Lincoln it could have been transferred to the newly built fortress at Chester. *II Adiutrix* left Britain, being relieved by *legio XX Valeria Victrix* in 88. Alternatively, the fortress could have been built and intended for *legio XX* succeeding Wroxeter as its base (Mason 2000).

The fortress was strategically located between two highland zones and could be supplied by sea. Its situation allowed it to continue for centuries (Webster 1985). The fortress could have initially served as a divider between the Brigantes and the Ordovices (Mason 2000: 17).

It seems that Chester was largely unoccupied for most of the 2nd century, as *legio* XX was engaged in the construction of Hadrian's and Antonine Walls. The fortress was refurbished in the early third century as the legion returned in full strength (Malone 2006).

Excavations and related objects.

Chester has a long history of studies and the site has been excavated several times during the 20th century, including:

- Small items were being produced in Chester, as the slags, off-cuts, casting jets and runners, and crucibles found in other places like Deanery Field (1928) and Princess Street (1939) show (Bayley 1995).
- Princess Street by Newstead and Droop in 1939.
- Goss Street by Richmond and Webster in 1948/9.
- Newgate/Pepper Street, in 1963-4 (Wilson & Wright 1964: 156; 1965: 204)
- Crook Street, in 1973-4: excavations also exposed an area of the legionary barrack block and part of a centurion's house (Mould , unpub.) .
- Northgate Brewery, 1974-5: late first and second century AD occupation including the intervallum road, a rampart building and a barrack (Ward & Strickland 1978).
- Abbey Green, in 1975-7, rescue excavation (McPeake *et al* 1980).
- Hunter St School, in 1979-81 took place in the barracks and the *fabrica* complex (Strickland 1983).
- 12 Watergate Street in 1985 (Ward 1988).

- *Tabernae* buildings west of the *principia*, in 1991. These could have been workshops, stores, or stables (Matthews 1995).
- 25 Bridge Street, 2001, situated to the east of the *praetentura* (Garner 2008).

During the 1960s, John Eames excavated extensively, as plans for redevelopment of Chester city centre prompted archaeological activity. His 1967-9 excavations at Old Market Hall included parts of the *principia,* barrack blocks, the *praetorium* and workshops and stores near it, as well as an elliptical shaped building of unknown function (Mason 2000). In the 1973 Goss Street excavations, Roman period buildings that could pre-date the construction of the fortress were found, but the finds are not supportive enough of a pre-Flavian occupation (Mason 2000). In the same excavations copper-alloy melting crucible fragments and scarce military equipment material, such as some *lorica segmentata* fittings (in contexts dating from mid 2nd to the 3rd century), were found (Lloyd-Morgan 1995). These objects were probably scrap material waiting to be recycled.

The objects analysed for this thesis are from seven of the sites above (see Fig. 4.4). Their association can be seen in Table 4.6, which shows contexts dated by pottery. A total of 42 objects were sampled and analysed, and consist of *lorica segmentata* fittings (18), belt plate fragments (7) horse harness equipment (4), apron fittings (2) *lorica squamata* (2), scabbard fragments (2), a helmet fitting, and plate fragments. The objects sampled date to different time periods: late 1st century AD (12 objects), first half of 2nd century (10),2nd century (7), 2nd to 3rd century (10), 3rd century (5), and 3rd to 4th century (5).

All the sampled objects are stored in the Grosvenor Museum in Chester.

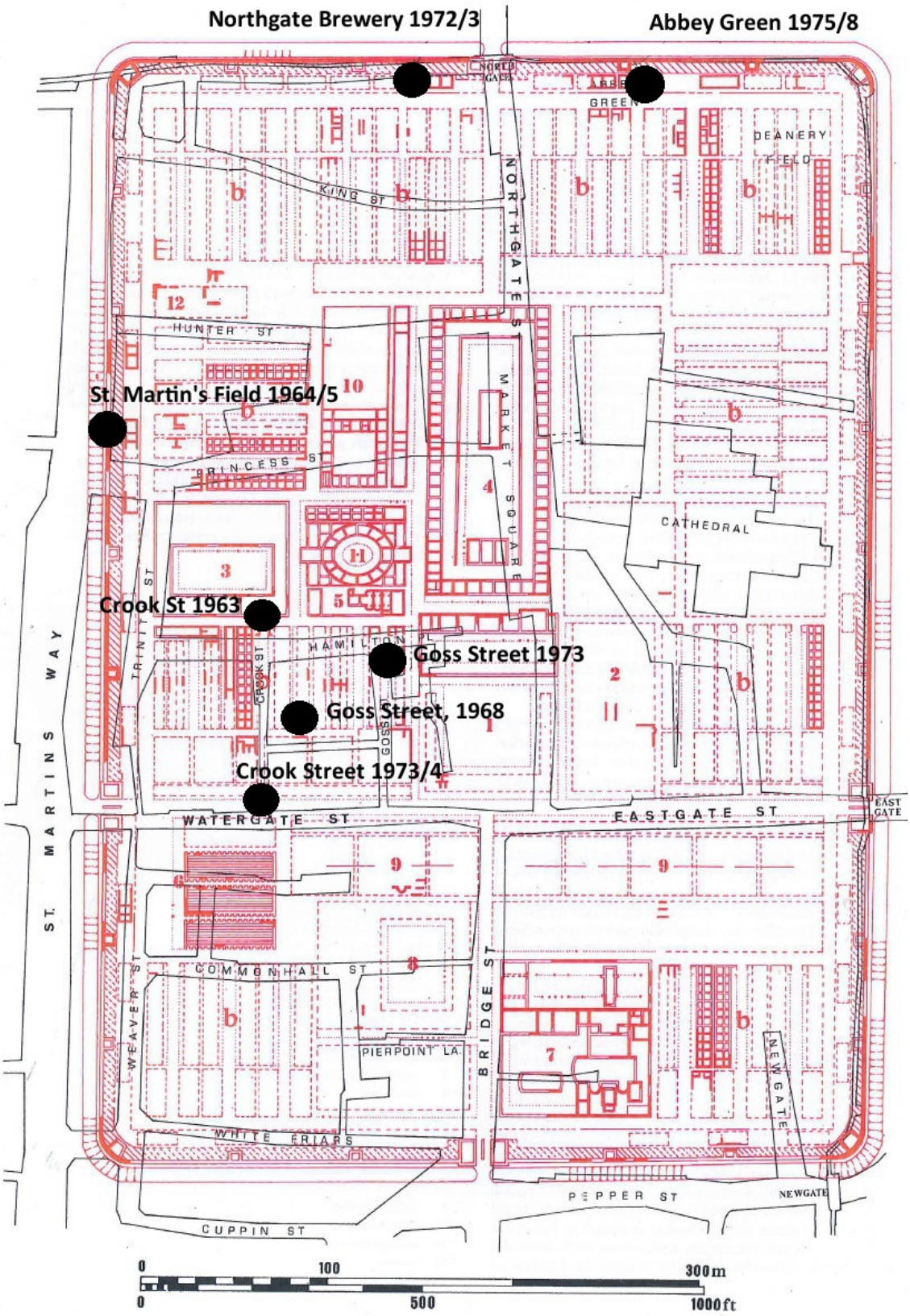
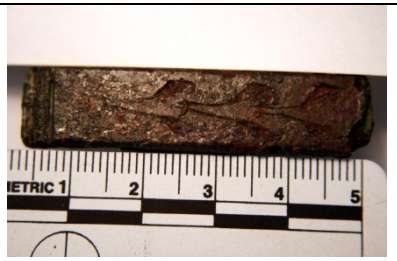


Figure 4.4 Chester. Excavations related to objects analysed. The legionary fortress is shown together with modern roads superimposed (after Mason 2000).

Sample	Description	Context		Excavation	Photograph
CHE3	Horse harness pendant	Latest pottery: AD240-400		Hamilton Place 1971	
CHE21	Fragment of dagger chape, plated	Late 1st-2nd century AD	Late 1st-2nd century AD	Goss Street 1968-9	
CHE57	Rectangular plate	Early-mid 3rd century and residual 1st & 2nd century pottery		Crook Street 1963-4	
CHE83a	Newstead *lorica segmentata* loop fastener	Late 2nd century- 3rd century AD	2nd - 3rd century AD	Goss Street 1973	

CHE83b	Newstead *lorica segmentata* loop fastener	Mixed layer	2nd - 3rd century AD	Crook Street 1973	
CHE108	Apron plate	4th century	Late 1st century AD	Hunter St School 1979	
CHE113	Apron pendant	4th century	Late 1st century AD	Hunter St School 1979	
CHE142	Lorica squamata	*tpq* mid 3rd century AD		Newgate/Pepper Street 1963-4	

CHE166	Belt plate fragment	Mixed, 4th century pottery	2nd century AD	Crook Street 1973-4	
CHE177	Scabbard runner	2nd century or later pottery		Old Market Hall 1967-9	
CHE261	*Lorica squamata*	AD120 to early 3rd century	2nd century AD	Goss Street 1968-70	
CHE349	Buckle (*lorica segmentata*?)	Late 1st – 2nd century AD	Late 1st century AD	Goss Street 1968-9	

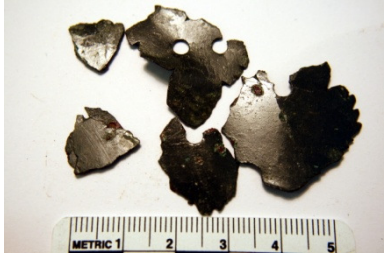
CHE393	Newstead *lorica segmentata* loop fastener	Residual	2nd - 3rd century AD	Goss Street 1973	
CHE424	Newstead *lorica segmentata* loop fastener	Residual	2nd - 3rd century AD	Northgate Brewery 1972-3	
CHE487	Newstead *lorica segmentata* loop fastener	Residual	2nd - 3rd century AD	Goss Street 1973	
CHE614	Chain	1st-2nd century AD		Old Market 1967-9	

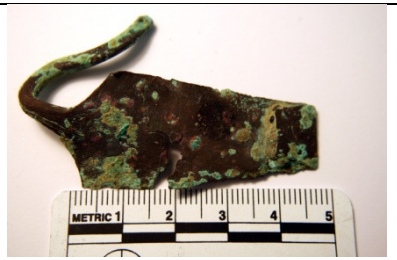
CHE684	Newstead *lorica segmentata* loop fastener	4th century AD	2nd century AD	Abbey Green 1975-8	
CHE701	*Lorica segmentata* strap buckle		Late 1st century AD	Crook Street 1974	
CHE755	*Lorica segmentata* lobate hinge	Early- mid 2nd century, with residual 1st century material	Late 1st century AD	Crook Street 1974	
CHE785	Crest support		Late 1st century AD	Crook Street 1974	

CHE992	Newstead *lorica segmentata* loop fastener	Second century or later	2nd - 3rd century AD	Old Market Hall 1967-9	
CHE1124	Mount	Late second century or later		Old Market 1967-9	
CHE1174	Newstead *lorica segmentata* loop fastener	*tpq 120+*	2nd century AD	Abbey Green 1975-8	
CHE1180	*Lorica segmentata* loop fastener	Late 1st-2nd century AD	2nd - 3rd century AD	Abbey Green 1975-8	

CHE1181	*Lorica segmentata* tie	c 250 or later	Late 1st-2nd century AD	Old Market 1967-9	
CHE1272	Open work terminal (scabbard slide?)	1st-2nd century AD	2nd century AD	Old Market Hall 1967-9	
CHE1513	*Lorica* buckle or strap attachment	1st-2nd century pottery	Late 1st century AD	Hunter Street School 1983	
CHE1516	Belt plate fragment	2nd century	2nd century	Goss Street 1973	

CHE1820	Belt plate fragments	3rd century pottery	2nd century AD	Abbey Green 1975-8	
CHE1829	*Lorica segmentata* hinged buckle plate	Residual	2nd century	Goss Street 1973	
CHE1833	Belt plate + 2 hooks	Residual	2nd century	Goss Street 1973	
CHE1834	*Lorica squamata* fragment	Residual	2nd-3rd century	Goss Street 1973	

CHE1844	Pendant	2nd century AD		Goss Street 1973	
CHE1850	Pendant, leaf shaped	2nd century AD		Abbey Green 1975-8	
CHE1855	Belt-plate fragment		2nd century	Goss Street 1973	
CHE1920	Belt plate with loop			Goss Street 1973	

CHE1945	*Lorica segmentata* hook	c120- 130/140 AD		Goss Street 1973	
CHE2024	Belt plate	Late 1st -2nd century	2nd century	Goss Street 1973	
2171	Pendant	Late 2nd century		Goss Street 1973	
CHE2186	Newstead *lorica segmentata* loop fastener	2nd century, 120+	2nd - 3rd century AD	Goss Street 1973	

CHE2197	Newstead *lorica segmentata* loop fastener	2nd century AD	Second half 2nd century	Goss Street 1973	
CHE2711	Pendant	Latest pottery: 3rd century AD		Abbey Green 1975	

Table 4.6 Sampled objects from Chester.

4.6 Kingsholm

The site of Kingsholm is situated where the Roman period Ermine Street, which links the area with Cirencester and Silchester, reaches the River Severn. Early Roman occupation at the site took place after AD49 with the construction of a fort or fortress. After two structural phases, in which it could have had different dimensions, the site was abandoned c.66/67. The site of the military base moved to Gloucester (1.5km away), to a more suitable crossing over the Severn (Hurst 1985).

Green (1942) proposed that Ostorius Scapula and *legio II Augusta* established a fortress at Kingsholm from 49 to 75, noting a connection between the Flavian pottery found at Gloucester and at Caerleon. The fortress could have been founded as a measure against the Silures, and following their defeat, Julius Frontinus would have taken the legion to its definitive base at Caerleon. A vexillation of *legio XX* could have moved from Colchester in 49, in order to participate in the Silurian campaigns before moving to Usk. Roman objects were found in Kingsholm in the 18th and 19th centuries, where it was not covered by houses (Green 1942). However, it was not until 1972 that larger scale excavations took place in Kingsholm Close (Hurst 1985). Excavations continued in the Dean's Way (1973), producing military equipment of the first century (Pitts 1985). Evidence of copper-smithing was found in a building that could have been a *fabrica* (Hurst 1985: 95). Horse-harness equipment and *lorica* fittings were found, but considered insufficient to inform about the types of units present. This excavation was followed by the 1981 discovery (at Sandhurst Road) of a pre-Flavian timber building.

Bayley (1985) analysed the military small finds from the 1972 Hurst excavations by energy-dispersive X-ray fluorescence (XRF). Since only surface analysis was performed on the objects, only alloy types could be obtained. Of the 18 objects analysed, which were mostly pendants and belt and baldric fittings, 12 were made of brass.

In 1983, the Gambier Parry Lodge site was excavated by Garrod (Hurst 1985). Timber buildings and ditches and later burials were found. This excavation yielded an important number of military objects (which remain unpublished) of the first century. All the objects from Kingsholm analysed in this thesis come from this site and are stored in Gloucester City Museum & Art Gallery. The assemblage sampled for analysis consists of 79 objects: horse harness fittings (26), *lorica segmentata* fittings (22), sheet and plate fragments (19), scabbard fittings (4), belt fittings (4), apron fittings (2), a shield binding fragment, and a ferule.

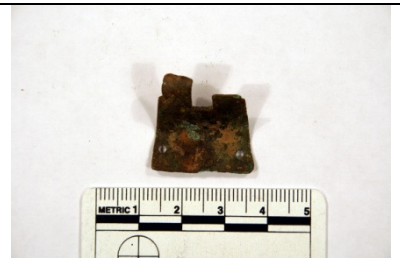
Sample	Description	Dating	Reference	Photograph
GLC48	Rosette	?	Unpublished	
GLC62	Corbridge *lorica segmentata* hinged plate	1st-4th century AD	Unpublished	
GLC121	Horse harness spectacle junction loop	Pre-Flavian	Unpublished	
GLC122	Horse harness strap mount	?	Unpublished	

GLC125	Roman G buckle, plated	1st century AD	Unpublished	
GLC127	Belt plate, plated	1st century AD	Unpublished	
GLC128	Corbridge *lorica segmentata* hinged plate fragment	1st-4th century AD	Unpublished	
GLC161	Rectangular plate (Newstead *lorica segmentata*)	2st-4th century AD?	Unpublished	

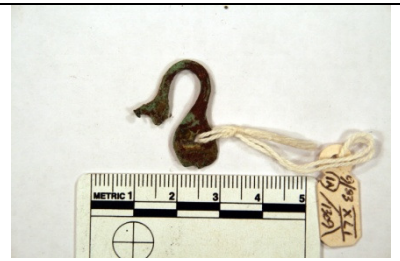
GLC192	Kalkriese *lorica segmentata* hinge?	Claudian	Unpublished	
GLC442	Catch plate pendant fragment?, plated	?	Unpublished	
GLC505	Riveted plate fragment (helmet tie loop plate?)	1st century AD	Unpublished	
GLC514	Rectangular hinge plate	?	Unpublished	

GLC538	Gilt harness strap fitting	Augustan?	Unpublished	
GLC813	Strap fastener	Augustan?	Unpublished	
GLC821	Corbridge *lorica segmentata* fitting	1st-4th century AD	Unpublished	
GLC822	Horse harness spectacle strap fastener	1st century AD	Unpublished	

GLC846	Shield binding	1st-2nd century AD	Unpublished	
GLC852	Horse harness junction loop, (Bishop Type 8)	Augustan	Unpublished	
GLC918	Horse harness junction loop, (Bishop Type 3g)	1st century AD	Unpublished	
GLC964	Corbridge *lorica segmentata* lobate hinge	1st-4th century AD	Unpublished	

GLC1046	Corbridge *lorica segmentata* fitting	1st-4th century AD	Unpublished	
GLC1085	Corbridge *lorica segmentata* lobate hinge	1st-4th century AD	Unpublished	
GLC1099	Kalkriese *lorica segmentata* hinged fitting	Claudian (1st century AD)	Unpublished	
GLC1139	Corbridge *lorica segmentata* hook fastener	1st-4th century AD	Unpublished	

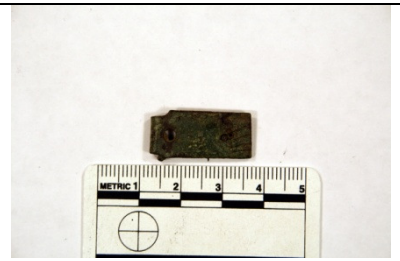
GLC1176	Horse harness junction loop (double-spectacle)	1st century	Unpublished	
GLC1199	Corbridge *lorica segmentata* hinged plate	1st-4th century AD	Unpublished	
GLC1206	Plated harness mount	1st century AD	Unpublished	
GLC1234	Buckle plate?	?	Unpublished	

GLC1298	Corbridge *lorica segmentata* hinged plate	1st-4th century AD	Unpublished	
GLC1308	Horse harness pendant, wolf's head terminal	Pre-Flavian	Unpublished	
GLC1309	Horse harness attachment for wolf's head pendant	Pre-Flavian	Unpublished	
GLC1315	Decorated strip, scabbard	1st century AD	Unpublished	

GLC1324	Cone shaped ferule, plated	?	Unpublished	
GLC1347	*Lorica segmentata*? fitting	?	Unpublished	
GLC1349	Horse harness phalera, plated	1st century AD	Unpublished	
GLC1376	Hinged plate	?	Unpublished	

GLC1446	Strap fastener (female)	Mid 1st century AD	Unpublished	
GLC1457	Button and loop fastener? - pendant fragment?	?	Unpublished	
GLC1489	Rectangular plate, plated	?	Unpublished	
GLC1533	Corbridge *lorica segmentata* hinged plate	1st-4th century AD	Unpublished	

GLC1550	Corbridge *lorica segmentata* fastener	1st-4th century AD	Unpublished	
GLC1573	Belt plate?	?	Unpublished	
GLC1611	Horse harness spectacle harness mount	1st –early 2nd century AD	Unpublished	
GLC1683	Scabbard chape	1st –early 2nd century AD	Unpublished	

GLC1685	Strip, from a scabbard	1st century AD	Unpublished	
GLC1921	Corbridge *lorica segmentata* hinged plate fragment	1st-4th century AD	Unpublished	
GLC1989	Corbridge *lorica segmentata* hinged plate	1st-4th century AD	Unpublished	
GLC2105	Corbridge *lorica segmentata* plate?	1st-4th century AD	Unpublished	

GLC2136	Binding with punched hole?	?	Unpublished	
GLC2147	Corbridge *lorica segmentata* buckle and plate fragment	1st-4th century AD	Unpublished	
GLC2148	Corbridge *lorica segmentata* hinged fitting	1st-4th century AD	Unpublished	
GLC2153	Horse harness crescent shaped pendant	Claudian (1st century AD)	Unpublished	

GLC2160	Horse harness junction loop	Augustan (1st century AD)	Unpublished	
GLC2161	Horse harness pendant, (Bishop Type 7)	Tiberio-Claudian (pre-Flavian)	Unpublished	
GLC2167	Pendant? Strap end?	?	Unpublished	

GLC2275	Riveted plate fragment	?	Unpublished	
GLC2290	Binding	1st-2nd century AD	Unpublished	
GLC2312	Corbridge *lorica segmentata* buckle plate	1st-4th century AD	Unpublished	
GLC2337	Horse harness triangular junction loop, (Bishop Type 7)	Pre-Flavian (1st century AD)	Unpublished	

GLC2356	Strip, from a scabbard suspension loop	Claudian (1st century AD)	Unpublished	
GLC2357	Strip	?	Unpublished	
GLC2359	Hinged plate (traces of plating)	?	Unpublished	
GLC2360	Horse harness junction Loop Type 1 (spectacled), fragment	Claudian (1st-early 2nd century AD)	Unpublished	

GLC2361	Horse harness junction loop/fastener (spectacled), fragment	Claudian (1st-early 2nd century AD)	Unpublished	
GLC2362	Horse harness junction loop (spectacled), fragment	Claudian (1st-early 2nd century AD)	Unpublished	
GLC2378	Corbridge *lorica segmentata* hinged plate	1st-4th century AD	Unpublished	
GLC2439	Corbridge *lorica segmentata*? hinged strap fitting	1st-4th century AD	Unpublished	

GLC2602	Binding	1st-2nd century AD	Unpublished	
GLC2677	Harness strap terminal	Claudian (1st century AD)	Unpublished	
GLC2680	Binding	1st-2nd century AD	Unpublished	
GLC2693	Horse harness junction loop (spectacled), fragment	Claudian (1st-early 2nd century AD)	Unpublished	

GLC2741	Strip, folded	?	Unpublished	
GLC2759	Corbridge *lorica segmentata* loop fastener	1st-4th century AD	Unpublished	
GLC2857	Pendant	Tiberio-Claudian (1st century AD)	Unpublished	
GLC2866	Rectangular plate	?	Unpublished	

GLC2933	Bishop Type I horse harness trifid pendant, silvered	Claudian (1st century AD)	Unpublished	
GLC2935	Corbridge *lorica segmentata* hook fastener	1st-4th century AD	Unpublished	
GLC2936	Rectangular plate	?	Unpublished	
GLC2943	Dagger frog?, plated	Tiberio-Claudian (1st century AD)	Unpublished	

Table 4.7 Sampled objects from Kingsholm

4.7 Kalkriese

Kalkriese is a wooded hill in north-western Germany, part of the Wiehengebirge range, and is located 20km north of Osnabrück. The southern part of the hill is flanked by a narrow sandy plain and a bog. Excavation has revealed finds and structure that make it likely to be at least one of the sites associated with the Varus disaster of AD9, where the legions *XVII, XVIII* and *XIX* were ambushed between the hill to the south and the moor to the north by the tribe of the Cherusci under Arminius (see Figure 4.5). The initial discoveries were by a metal detectorist (Clunn 2005). This was followed by a more systematic survey and the plotting of the 'hits' (cf Fig. 4.5) and which in turn determined the subsequent excavation and so recovery of artefacts (cf Fig. 4.6).

In 1989 excavations began at the Oberesch field (Figure 4.6), at the middle of the long path following the contour of the base of the hill. A 2m high turf and sand rampart was built around part of the hill to aid an ambush against the passing Romans. This site concentrates most of the finds (more than 5000), but the conflict extended to several places along the base of the hill, as skirmishes developed following the main battle (Rost & Wilbers-Rost 2010). Among the military equipment iron projectiles, spearheads and *pila* parts were found, as well as copper-alloy buckles, shield binding and helmet, apron, scabbard and *lorica segmentata* and *hamata* fittings (Franzius 1995).

However, post-battle processes are fundamental to understanding the type of military objects in the archaeological record at Kalkriese. The concentration of the finds seems to be related more to rescuing wounded men, looting and disposition of the defeated soldiers than to the intensity of the fighting (Rost 2009).

According to the excavators, most of the equipment was looted immediately after the battle, and what was left for the archaeological record was in a fragmentary state. A significant proportion of the copper-alloy finds is constituted by shield binding fragments (Harnecker 2008; 2011). It seems that the victorious Germans gathered metal fragments near the ramparts and folded them for easier transportation and later re-use (Rost & Wilbers-Rost 2010).

Due to curatorial restrictions, most of the sampled objects belong to the sheet binding category, in the form of shield binding and parts of *litui,* Roman military trumpets (Meucci 1989). However, two copper-alloy helmet fittings and a belt buckle could be sampled.

All the objects found at Kalkriese are stored in the site museum, Varusschlacht, 22kms north of Osnabrück.

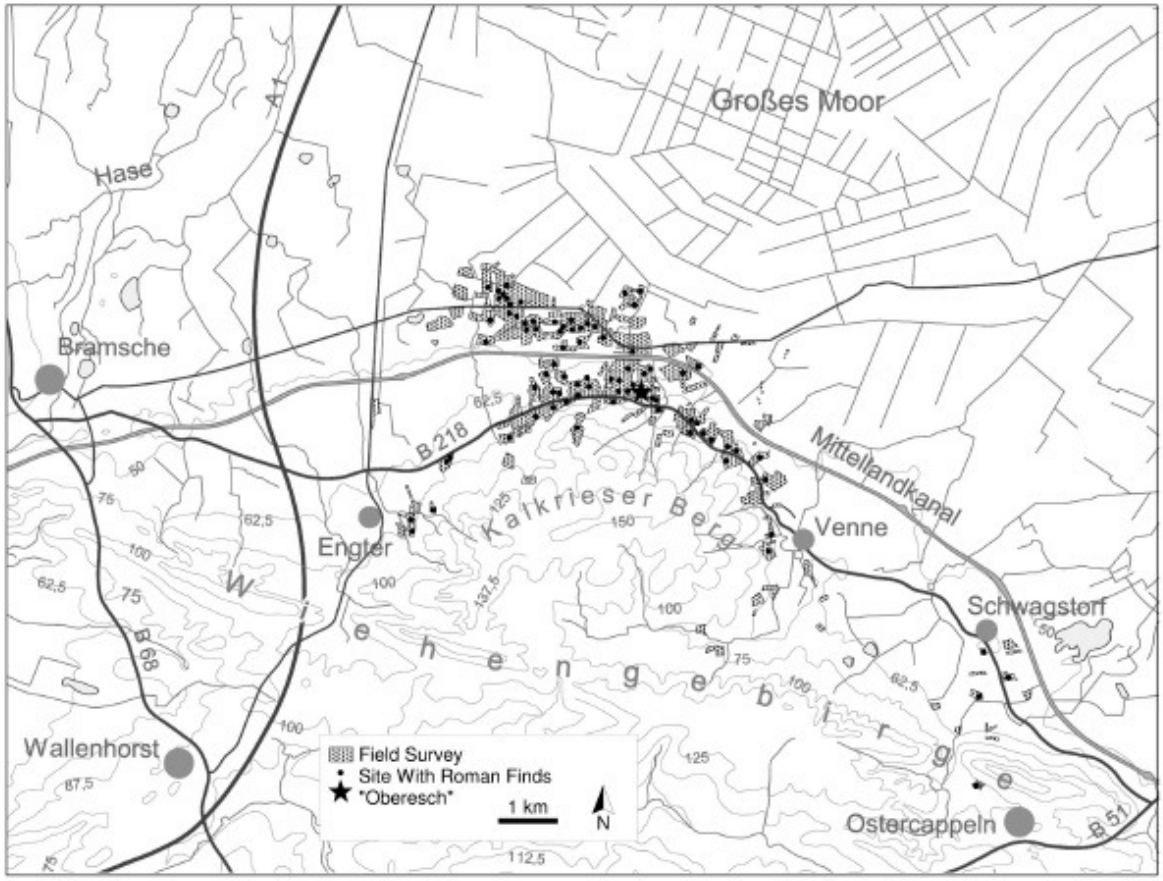


Figure 4.5 The surveyed areas along the Kalkriese Berg (from Wilbers-Rost 2009).

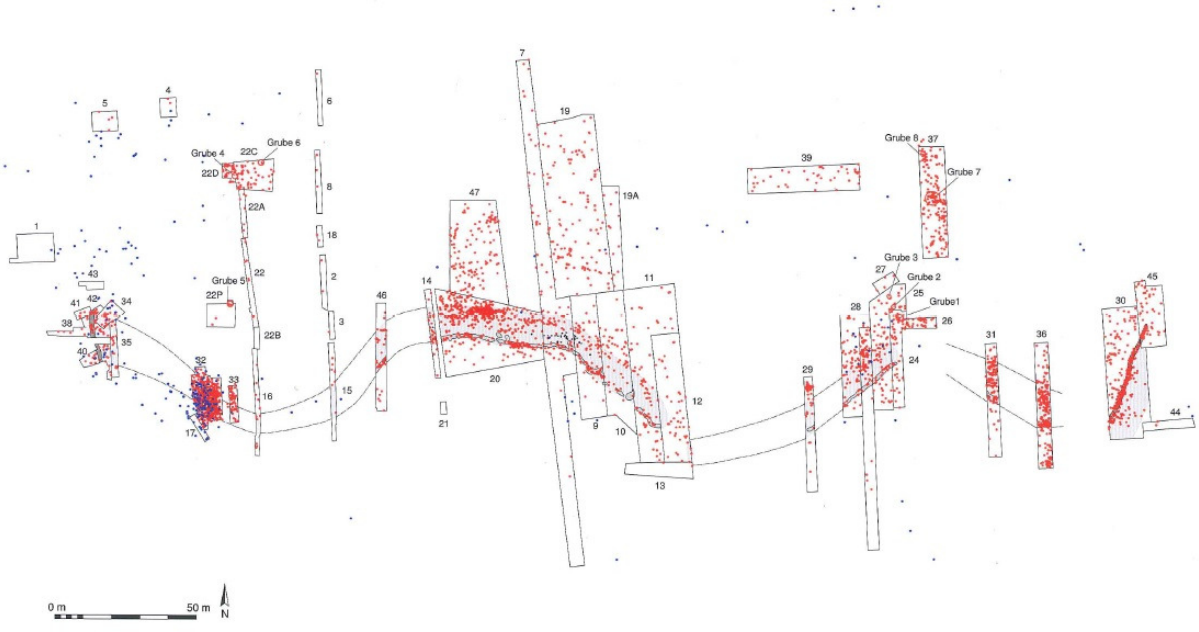
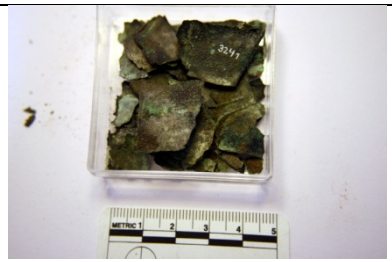
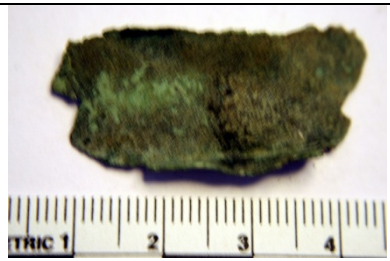


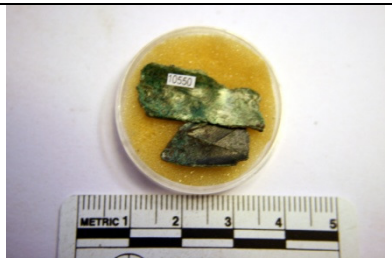
Figure 4.6 The distribution of finds at the 'Oberesch' site, where most finds were concentrated (from Rost & Wilbers-Rost 2012).

Sample	Description	Dating	Reference	Photograph
K186	Sheet fragment	Late 1st century BC – Early 1st century AD	Unpublished	
K742	Shield Binding	Late 1st century BC – Early 1st century AD	Harnecker 2008, Kalkriese 4, No. 73	
K956	Shield Binding	Late 1st century BC – Early 1st century AD	Harnecker 2008, Kalkriese 4, No. 84	
K2000	Shield Binding	Late 1st century BC – Early 1st century AD	Harnecker 2008, Kalkriese 4, No. 37	

K2002	Shield Binding	Late 1st century BC – Early 1st century AD	Harnecker 2008, Kalkriese 4, No. 78	
K2030	Lituus fragment?	Late 1st century BC – Early 1st century AD	Unpublished	
K3223	Shield Binding	Late 1st century BC – Early 1st century AD	Harnecker 2008, Kalkriese 4, No. 81	
K3241	Shield Binding	Late 1st century BC – Early 1st century AD	Unpublished	

K3797	Shield Binding	Late 1st century BC – Early 1st century AD	Harnecker 2008, Kalkriese 4, No. 70	
K5610	Belt Buckle	Late 1st century BC – Early 1st century AD	Harnecker 2008, Kalkriese 4, No. 118	
K7094	Shield Binding	Late 1st century BC – Early 1st century AD	Unpublished	
K9847	Shield Binding	Late 1st century BC – Early 1st century AD	Harnecker 2008, Kalkriese 4, No. 79	

K9900x	Lituus fragment	Late 1st century BC – Early 1st century AD	Unpublished	
K10107	Lituus	Late 1st century BC – Early 1st century AD	Unpublished	
K10412	Lituus	Late 1st century BC – Early 1st century AD	Unpublished	
K10413	Lituus	Late 1st century BC – Early 1st century AD	Unpublished	

K10282	Lituus	Late 1st century BC – Early 1st century AD	Unpublished	
K10550	Shield Binding	Late 1st century BC – Early 1st century AD	Unpublished	
K10597	Lituus	Late 1st century BC – Early 1st century AD	Unpublished	
K11816	Shield Binding	Late 1st century BC – Early 1st century AD	Harnecker 2008, Kalkriese 4, No. 88	

K1318143-S6	Helmet crest holder	Late 1st century BC – Early 1st century AD	Unpublished	
K13695/E	Shield Binding	Late 1st century BC – Early 1st century AD	Harnecker 2008, Kalkriese 4, No. 46	
K21543	Lituus fragment	Late 1st century BC – Early 1st century AD	Unpublished	
K22373	Helmet knob	Late 1st century BC – Early 1st century AD	Harnecker 2011, Kalkriese 5, No 2110	

K22622	Shield Binding	Late 1st century BC – Early 1st century AD	Harnecker 2011, Kalkriese 5, No 2081	
K25925	Shield Binding	Late 1st century BC – Early 1st century AD	Unpublished	
K26305	Shield Binding	Late 1st century BC – Early 1st century AD	Unpublished	
K26855	Shield Binding	Late 1st century BC – Early 1st century AD	Unpublished	

K28504	Socket	Late 1st century BC – Early 1st century AD	Unpublished	
K33801	Sheet fragment	Late 1st century BC – Early 1st century AD	Unpublished	
KProsp6_29/6/102	Shield Binding	Late 1st century BC – Early 1st century AD	Unpublished	

Table 4.8 Sampled objects from Kalkriese

4.8 The location of the legions

The sequence of locations for the *legio II Augusta* and *legio XX Valeria Victrix* before arriving to their permanent bases in Britain is not clear. Precise dating of known locations along with numerous hypothesized locations complicates the picture. Similarly detachments of legions, or vexillations, worked as an aid in particular areas of the empire without leaving their bases unoccupied (Casey 2002).

4.8.1 *Legio II Augusta*

The origins of *II Augusta* are not known, and its history before being taken to Britain is not clear (Keppie 2002). It could have been a Second Legion raised in 48BC by Caesar, another with the same number formed by the consuls Hirtius and Pansa, or created by Octavian to replace legions lost during the civil war. A legion with the same numeral, *II Gallica*, was present in Gaul (Orange) and later transferred to Spain during the time of Augustus. There it could have received the title *Augusta*. This legion was sent beyond the Rhine in AD9 in the aftermath of the Varus disaster (to Marktbreit or Haltern) but did not remain in the area. The legion could have been garrisoned at Aulnay, France, before moving to Strasbourg in AD14, with a brief period at the double fortress of Mainz with *legio XIIII Gemina* (Keppie 2002: 17-20).

Legio II Augusta left Strasbourg for Britain under its commander, Vespasian (Brewer 2002a), in or before 43 and separated from the other legions of the invading army after Colchester/Camulodunum was taken. Vespasian then campaigned against the Durotriges until 47, including the capture of Ham Hill in 45. Several possibilities have been suggested as to where the legion was based during this time and in the following years. For the Durotrigan campaign, the legion could have been at Chichester under Aulus Plautius. Then it gradually moved across the south until it was established at Exeter and later possibly at Lake Farm from 48 to 55 (Webster 1958; Manning 2002). It has also been speculated that Alchester was a base of the legion in this period (Sauer 2005). The tombstone of a veteran suggests that the 'legionary' fortress of Alchester, whose construction is dated to 44 at the earliest by dendrochronology, may have been the base for the 2nd legion following the start of the invasion (Bidwell 2007).

It seems that it was common for Claudian and Neronian commanders to divide legions and combine detachments in the same place (Jarrett & Webster 2002). By the mid 50s, the legions were divided between Exeter and Gloucester while *legio XX* was at Usk. Alternatively, the legion could have moved from Exeter to Gloucester from 66 to 75. There is a third possibility: Bidwell and Boon

(1976) argued that *legio II* remained at Exeter until the 70s, before becoming established in its long term base, Caerleon, in 74 or 75 (Brewer 2002:2).

The legion later helped to build Hadrian's Wall (together with the legions XX and VI), and participated in the conquest of lowland Scotland and the construction of the Antonine Wall (Casey 2002), as is epigraphically attested on distance slabs (Breeze 2002).

In the third century, according to Fulford (2002), it could have moved to Cardiff to respond to raids coming from the sea. In the late fourth century it moved to Richborough, according to the *Notitia Dignitatum*, but a (residual) presence at Caerleon could still have been possible (Brewer 2002).

4.8.2 *Legio XX Valeria Victrix*

The history of *legio* XX is not certain before AD6, when the legion was taken from the Balkans (Illyricum) to Carnuntum on the Danube, as Tiberius was preparing for a campaign against the Marcommani (Pollard & Berry 2012). A *legio XX Siciliana* is known to have settled at Beneventum in southern Italy, probably in 36BC. The same legion, or a new one, could have participated at Actium. *Legio XX* is then thought to have been present in Spain for the Augustan campaigns of 26-25BC, and could have remained there until 19BC. It was then probably taken to the Alpine campaigns of 16-15BC and the Pannonian Wars of 13-9BC under Tiberius. It is known that by AD6 the legion was serving in Illyricum. However, it had to move again, to Pannonia and Dalmatia to help suppress the revolt of AD6, being based probably at Siscia and Burnum during this time (Malone 2006).

In the wake of the Varus disaster of AD9, Tiberius took *XX Valeria Victrix* and *XXI Rapax* from the Danube to the Rhine (Pollard & Berry 2012: 99). The legion could have been based at Köln and then at Neuss, together with *legio I* and could have taken part in the punitive expeditions of Germanicus and Caecina.

According to Webster (1985a) the 20th legion remained at Colchester after arriving in Britain. It was later moved by Ostorius Scapula to Kingsholm to protect the crossing of the lower River Severn and to fight the Silures under Caratacus. The legion, or part of it, moved to Usk in the mid-50s, where it stayed until 66. The legion then could have moved to Wroxeter, from where *legio XIIII* left Britain (Brewer 2002). At the same time *legio II* probably moved from Exeter to Gloucester to fill this new gap. But if *legio II* was moved directly from Exeter to Caerleon, then Gloucester was probably another base of *legio XX*.

The legion was probably divided across several bases at this point, and vexillations were called to support Vitellius in the civil war following Nero's death. The legion was taken by Agricola to campaign in the north, with probable vexillations at Carlisle (Tomlin 1992) and Corbridge (Malone 2006). Between 83 and 86, during Agricola's campaign in Scotland, the legion could have initiated the construction of the fortress at Inchtuthil. The legion returned from Scotland c.86 and established a base at Chester (Mason 2000).

Chester was significantly demilitarised in the 120s, as the legion left for the north to participate in the construction of the two walls (Malone 2006). It is possible that soldiers of the 20th legion were divided between Newstead, Carlisle and Corbridge in the latter half of the second century. Vexillations of *XX Valeria Victrix* were present at Lyon on the losing side fighting Septimius Severus, and returned to Chester afterwards in the early 3rd century. Together with *II Augusta, legio XX,* participated in the Severan campaigns in northern Britain

Vexillations are known to have been in mainland Europe from the mid-third century. However, there was continuous occupation at Chester into the 4th century AD (Pollard & Berry 2012).

4.8.3 *Legiones XVII, XVIII* and *XIX*

Little is known of the early years of these three legions, but they are believed to have been created by Octavian in 41-40BC (Keppie 1995). They were probably destroyed at Kalkriese, in the Teutoburger Wald in AD9 by the tribe of the Cherusci commanded by Arminius. Mommsen and Hardy first thought that the legions were created in Rome in AD6, but later it was suggested that they were created by Octavian before Actium (Parker 1928).The existence of *legio XVII* has not been explicitly attested by any source, but is believed to have been present in the Teutoburg Forest, because there are no XVII-XIX numerals after AD9 in the sequence of legions (Keppie 1995).

Legio XVIII was probably based at Xanten, as the tombstone of centurion Marcus Caelius suggests (Junkelmann 1986), and participated in Tiberius' campaign of AD6 against the Marcomanni. Other inscriptions from Augustan times informing about the legion are those of a soldier serving in a *legio* XVIII during the time of Augustus (*CIL* XIV 2950, found in Palestrina, south of Rome); and another found at the colony of Ateste (*CIL* V 2499), south-west of Padova, commemorating a soldier of the legion (Keppie 1995).

There are veterans known of a *XIX* legion near Pisa following the Battle of Actium. *Legio XIX* was probably involved in the conquest of Raetia (15BC) and could have had Dangstetten, on the

Upper Rhine, as its base (Junkelmann 1986). The legion could then have moved to Köln or Neuss, and later to Haltern, where an ingot stamped with the name of the legion was found (Keppie 1998).

4.9 Conclusion

This chapter presented the assemblages selected for analysis and summaries of the sites to which the assemblages belong and their excavation. The chapter ends with a discussion on the location of the legions assumed to be associated with the assemblages analysed. The following chapter presents the results of the scientific analysis of the assemblages described above employing the techniques detailed in Chapter 3.

Chapter 5: The analysis of the results

5.1 Introduction

This chapter presents the results of the metallurgical analysis for all the objects in Chapter 4 that contribute to the characterisation of the assemblages.

Characterisation involved first the chemical analysis of all the objects by AAS. Approximately a third of the total number of samples were also chemically and metallographically analysed by SEM-EDS and optical microscopy. First, the AAS and EDS chemical analysis results are compared, then the chemical and metallographic results are presented, followed by a multivariate analysis on the compositional data. Finally, a summary of the results is provided.

The results are described on a site by site basis first in the following order:

1. The proportion of copper-alloy types of each assemblage (defined by the quantities of tin, zinc and lead obtained by AAS). In the assemblages with a significant number of brasses, the distribution of zinc is shown, as well as a biplot showing the behaviour of tin v. zinc.
2. Combinations of pairs of trace elements (obtained by AAS) to show correlations, or possible groupings based on differences in trace element quantities. For these pairings, the trace element percentage values were scaled to the copper, since they are metallurgically associated with it in order to compensate for the different amounts of copper in the objects due to the presence of zinc and tin. In this way, all the objects are comparable and pairs of elements can be plotted against each other.
3. Metallographic analysis of etched sections (for the purposes of optical microscopy) and scanning electron microscope images, describing grain size, degree of deformation, microstructure features and plating.

After presenting the results for the individual sites, the complete corpus of objects is then considered in a similar sequence so as to compare sites and alloy type.

Some of the graphs contain information coded by time period, with the following key:

1. early 1st century
2. mid first century to early 2nd century
3. 2nd century
4. 3rd century
5. 3rd to 4th century

The final section of the chapter shows the results of multivariate analysis (principal component analysis followed by discriminant analysis) of the AAS data for all the sites by considering five elements associated with the copper: silver, nickel, cobalt, arsenic and antimony.

5.2 The AAS and EDS results

The results for the 11 elements analysed using AAS can be seen in tables for each site (A2.1-A2.7), where alloy type classification (based on the criteria described in Section 3.2.1.1) is also displayed. Whenever a quantity is preceded by the "<" sign it indicates that the value shown is below the limit of detection for a particular element for that particular sample.

The comparison of the results obtained by AAS and those by EDS is best when considering major elements (copper, zinc, tin, and lead), since EDS is not a trace element technique (see Table A4.1-7). Differences in the results between the two techniques are expected in the case of lead, since this metal is not soluble in copper. The presence of lead is localised in certain areas, which makes small area analysis techniques, such as EDS, less reliable than AAS since the latter is a bulk analysis technique. Differences in the measurement of copper are less than 5% between the two techniques for the great majority of the samples. In the case of zinc, the agreement between the two techniques is within 10% when the measured values are above the limit of detection for EDS. Of the major elements, the only variation was found for tin, where generally slightly lower values were obtained by EDS due to calibration.

AAS is a technique that is more sensitive than EDS by more than two orders of magnitude, and thus provides more reliable measurements of the minor and trace elements analysed in this thesis. The difference in sensitivity is the reason for the high variations found in some of the trace element values for some of the samples when the techniques are compared.

Results by site

5.3 South Cadbury Castle

5.3.1 AAS Results (Table A2.1)

5.3.1.1 Alloy type

The AAS results for South Cadbury Castle can be seen in Table A2.1 for the six objects analysed. Half of the objects analysed are brasses, the rest being gunmetal objects and a bronze. Of the four *lorica segmentata* rosettes analysed, three of them are low tin gunmetal objects containing

between 15.2% and 17.5% zinc and 2.5% and 4.6% tin. A fourth rosette has a similar amount of zinc, but also contains enough tin to be considered a gunmetal. The shield binding fragment analysed is a pure brass with 21.8% zinc content. The horse harness junction is a 7.4% tin bronze with a very low zinc content.

5.3.1.2 Trace elements

Whilst the sample size for South Cadbury Castle is small (8 objects), some trends can still be noted when certain trace elements are plotted. Three pairs of elements seem to be positively correlated: antimony-arsenic, arsenic-silver, and antimony-silver (Figs. 5.1 to 5.3). Since these elements are associated with the copper, these correlations suggest a common source for the objects.

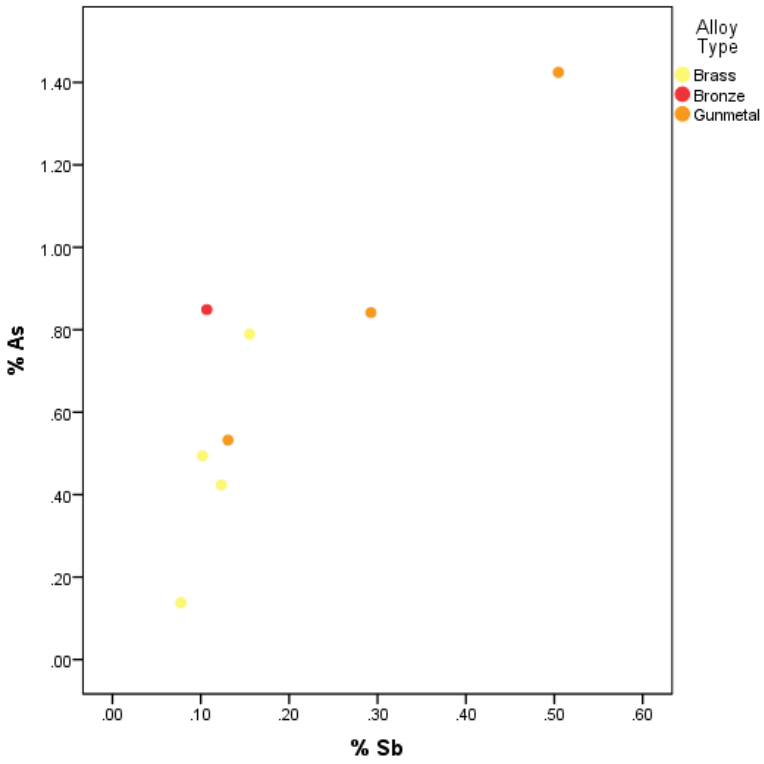


Figure 5.1 South Cadbury Castle. Antimony v. arsenic bivariate plot, with both elements re-scaled to the copper.

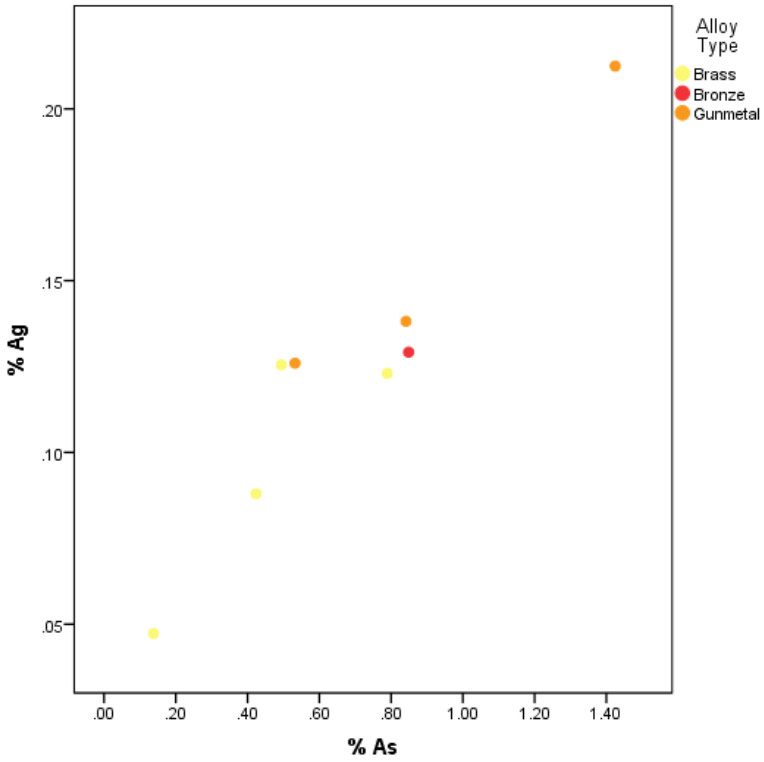


Figure 5.2 South Cadbury Castle. Arsenic v. silver bivariate plot, with both elements re-scaled to the copper.

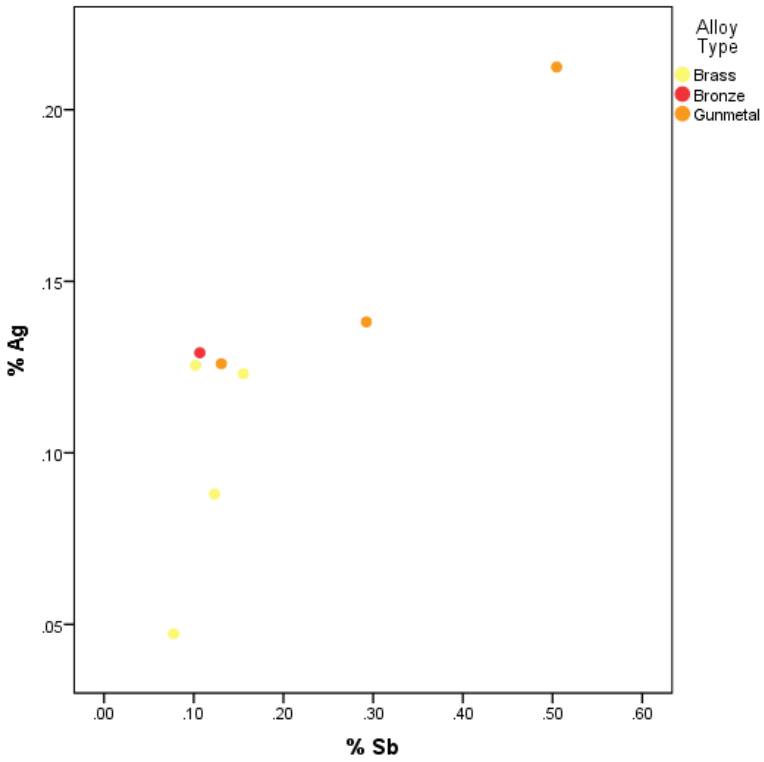


Figure 5.3 South Cadbury Castle. Antimony v. silver bivariate plot, with both elements re-scaled to the copper.

5.3.2 Metallography

CC113 (Fig. 5.4)

Upon etching, this shield binding fragment shows a single-phased microstructure constituted by relatively regular grains with twinning, indicating previous cycles of working and annealing. Some of the grains show strain lines as well, which are indicative of the fact that the last stage of manufacture was cold working. Small lead inclusions are apparent, as this metal is insoluble in copper.

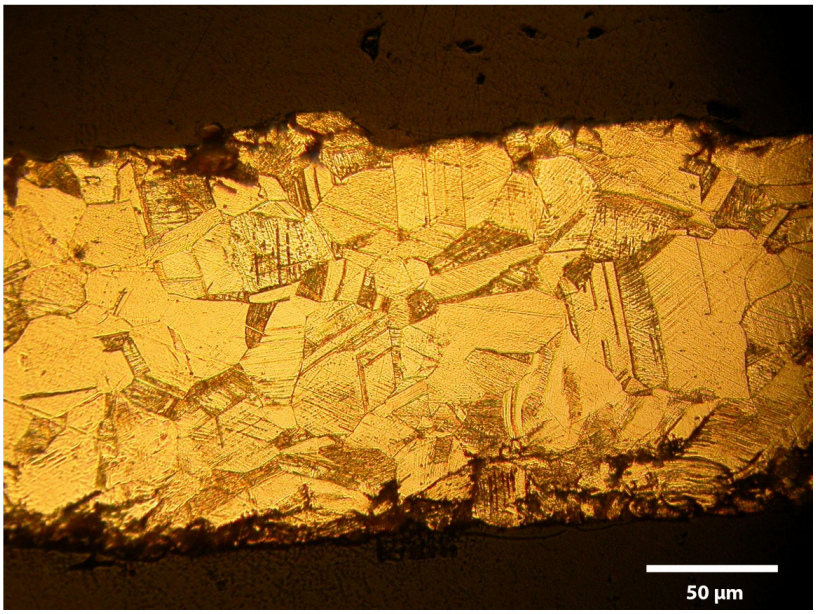


Figure 5.4 CC113.

CC136 (Fig. 5.5)

This sample was taken from a *lorica segmentata* lobate hinge. It shows a single phased brass microstructure, with considerably smaller grains, and with a much higher degree of deformation when compared to the shield binding fragment (CC113). Some of the grains are elongated, as the material flowed parallel to the direction of deformation. Twinning is widely present in the sample and points again to a history of cycles of working and annealing. Lead inclusions are visible in the form of stringers (as they are independent of the process of grain recrystallization, being insoluble in copper) parallel amongst themselves and all of them following the general direction of deformation.

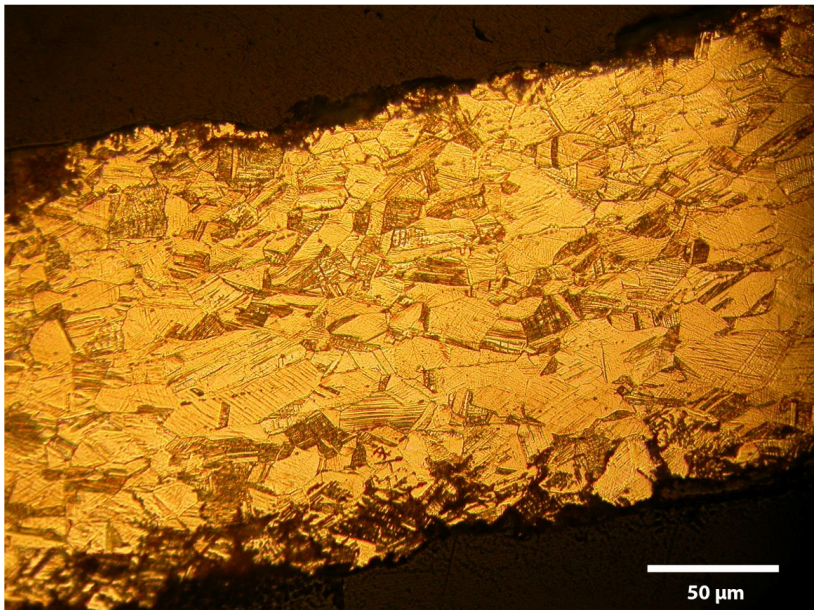


Figure 5.5 CC136.

CC153 (Fig. 5.6)

This sample was taken from a decorated rosette, and the sheet it was made from is very thin, a fact that corresponds in the microstructure to very deformed and elongated 30-40µm grains with strain lines in the direction of deformation. The edges of the sample are corroded, and since the bulk is very thin, corrosion can penetrate deeply, also aided by the high energy zones along grain boundaries and strain lines. The result is inter- and trans-granular corrosion, as the grain structure is visible even in the un-etched condition with corrosion products occupying grain boundaries and slip lines.

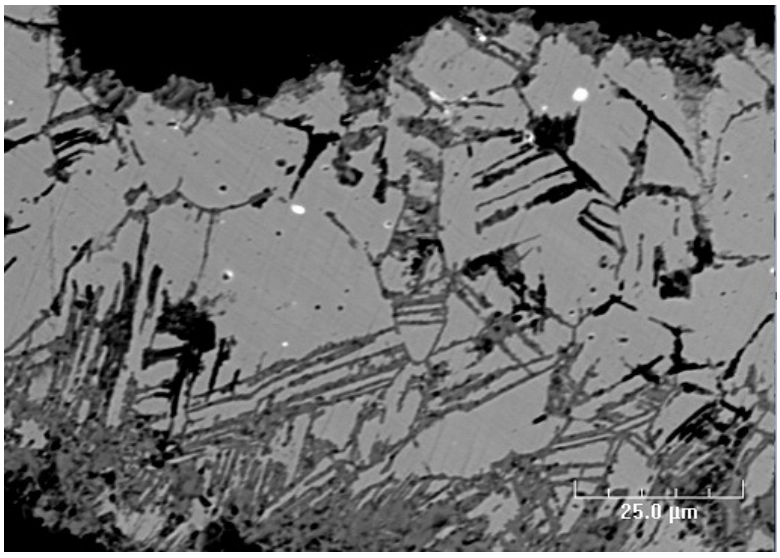


Fig 5.6 CC153, corrosion revealing internal structure, unetched condition.

5.4 Ham Hill

5.4.1 AAS results

5.4.1.1 Alloy type

Brass is the alloy best represented in the Ham Hill objects (Figs. 5.7 and A2.3), with more than 40% of the objects being made of this alloy. The brass objects contain an average of 21.6% zinc and are mainly horse harness, apron and *lorica segmentata* fittings, together with a *lorica squamata* scale. Gunmetals and bronzes account for approximately 25% each of the assemblage analysed. All of the shield binding fragments and studs analysed, and a buckle, are made of bronze. All the gunmetal objects belong to horse harness equipment and are leaded. The rest are two unalloyed copper objects: a stud and a gilded decorated roundel (not analysed by AAS).

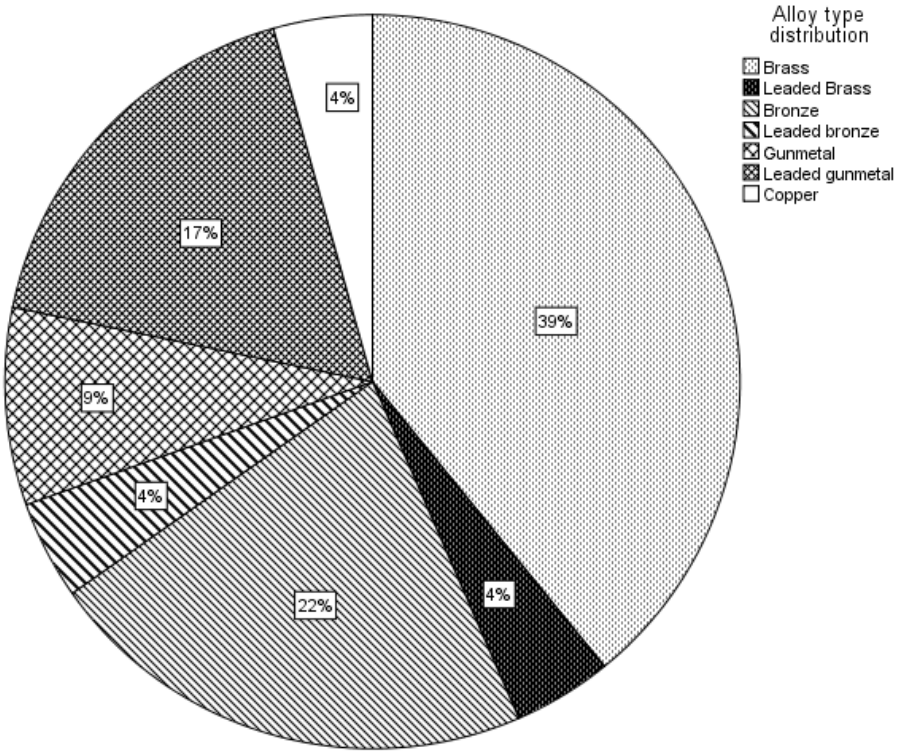


Figure 5.7 Distribution of alloy type in the objects from Ham Hill.

5.4.1.2 Trace elements

When antimony and arsenic are plotted against each other (Fig. 5.8) no correlation is seen. However, the brasses form a separate group from the other alloys as they contain a lower amount of both these elements, which also happens when te values are scaled to the copper. The number of

bronzes is not large but it seems that they tend to contain a higher amount of antimony than the brasses and gunmetals.

In the case of antimony and cobalt (Fig. 5.9), when cobalt is detectable (over 0.02% cobalt in the graph), there is a correlation between the two elements (R^2=0.872 obtained by linear regression). The same situation is seen in the nickel v. silver (Fig. 5.10, R^2=0.708 after removing three outliers), but weaker for antimony v. silver plots (Fig. 5.11, R^2=0.472) for most alloy types, except bronze.

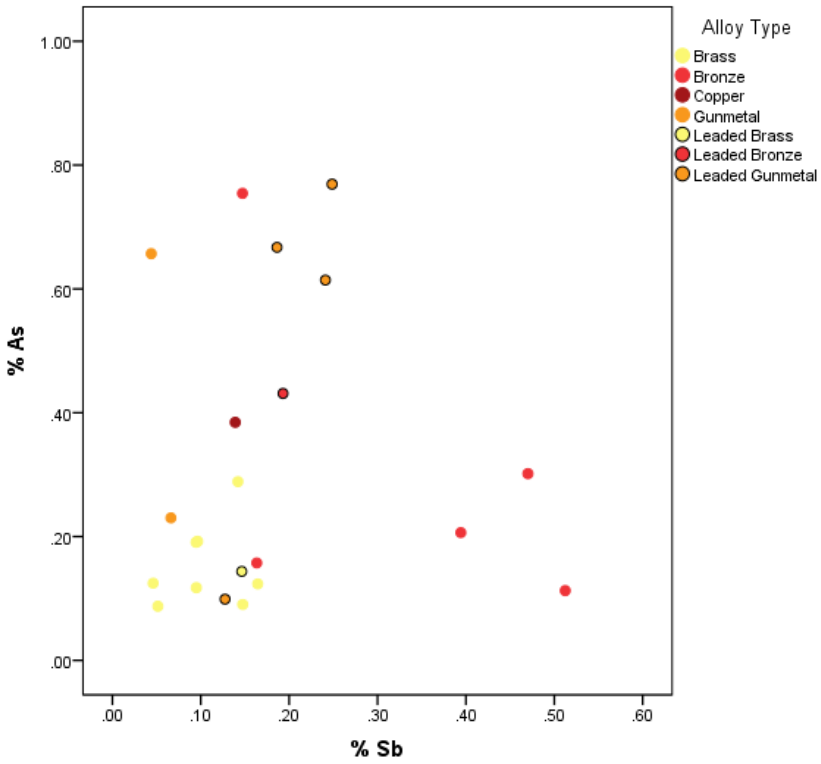


Figure 5.8 Ham Hill. Antimony v. arsenic bivariate plot, with both elements re-scaled to the copper.

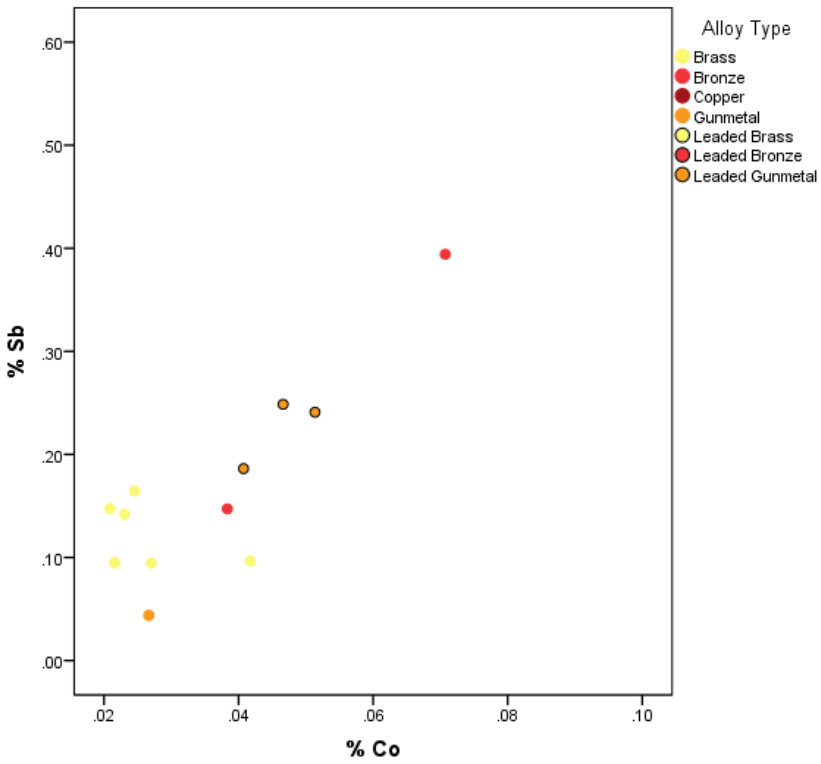


Figure 5.9 Ham Hill. Cobalt v. antimony bivariate plot, with both elements re-scaled to the copper.

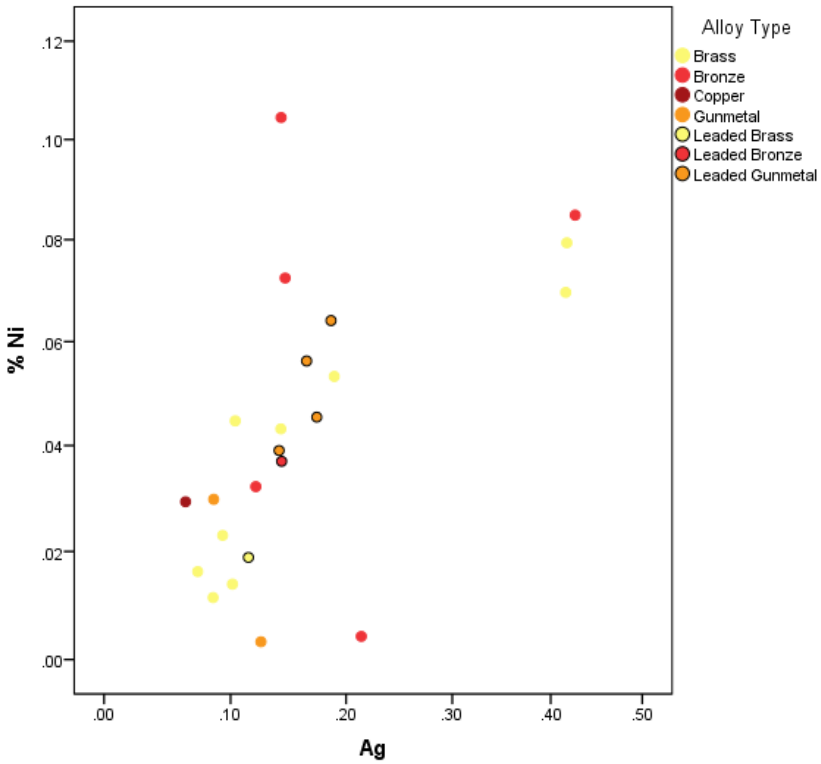


Figure 5.10 Ham Hill. Silver v. nickel bivariate plot, with both elements re-scaled to the copper.

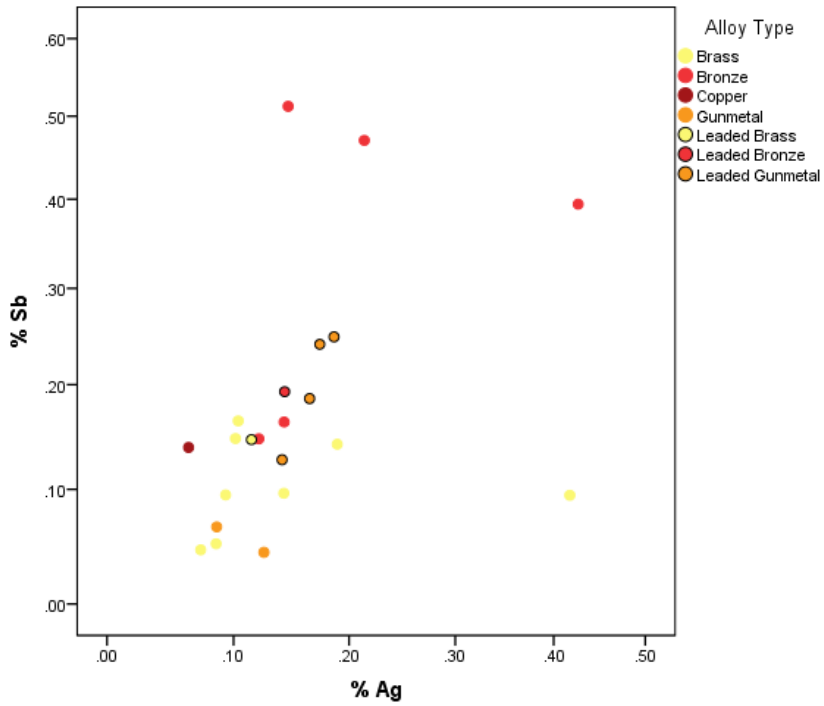


Figure 5.11 Ham Hill. Silver v. antimony bivariate plot, with both elements re-scaled to the copper.

5.4.2 Metallography

Ham Hill E16 (Fig. 5.12).

This sample was taken from near the tip of the hook of a *lorica segmentata* tie loop, and while it shows some similarities with other objects made from sheet metal, such as a single-phased brass microstructure with very well defined twins indicating repeated cycles of working and annealing, it presents very large crystals (80µm) and does not show slip lines. This means that the last part of the manufacturing process did not affect this part of the original metal sheet from which the *lorica* tie loop was manufactured. This microstructure indicates that the *lorica* tie would have been rather weak and flexible given its intended task.

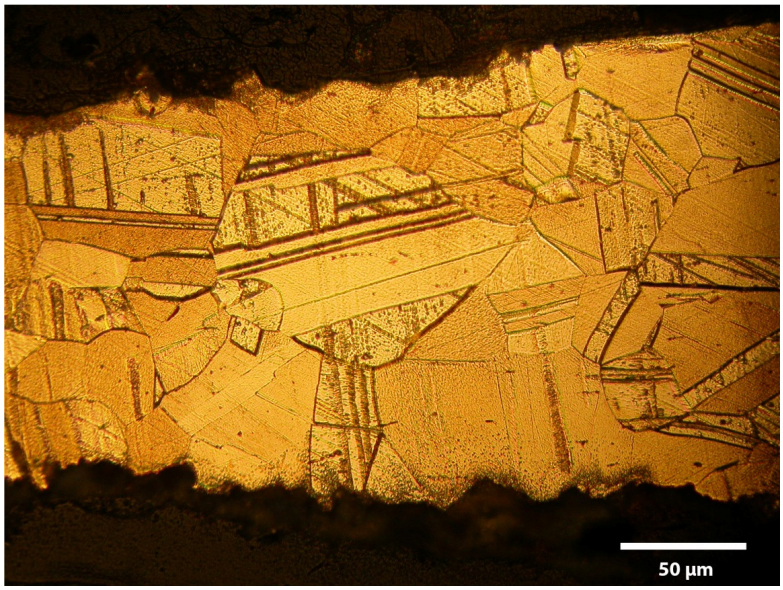


Figure 5.12 HamH E16.

Ham Hill A1276 (Fig. 5.13).

This is a group of three armour scales (*lorica squamata)*, of which two are tinned and joined by two wires (Fig. A1.19a-b). Each scale bears six holes, two on each side and two at the top (Fig. 5.14). This configuration is a part of the well-known large group of scales from a single *lorica* found in 1885 (Gray 1910), in which each scale is attached to only two other scales one on each side, with one side on top of the adjacent scale, making the armour relatively flexible even if not very useful against upward slashes like later semi-rigid styles (Bishop & Coulston 2006: 140). The two holes on the top were used to attach the scale to a leather backing. The original appearance of the metal would have given the armour an alternate pattern of silver and gold coloured scales.

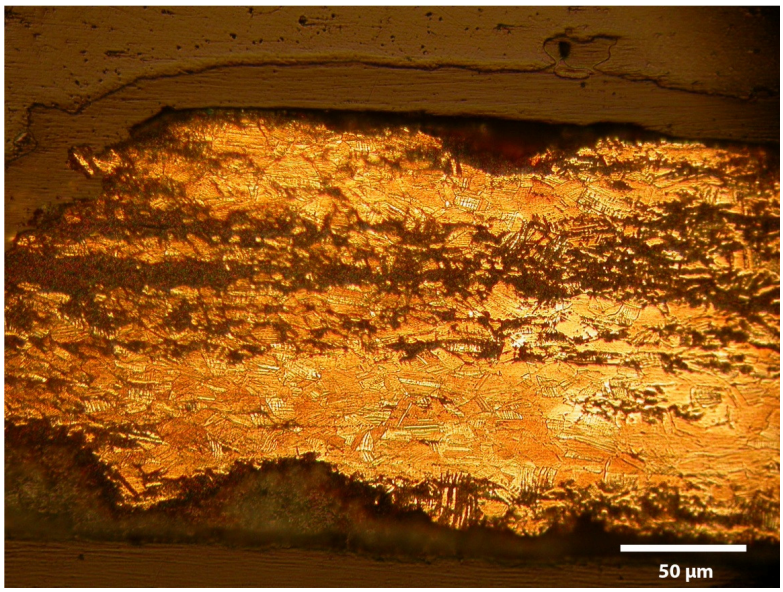


Figure 5.13 HamH A1276.

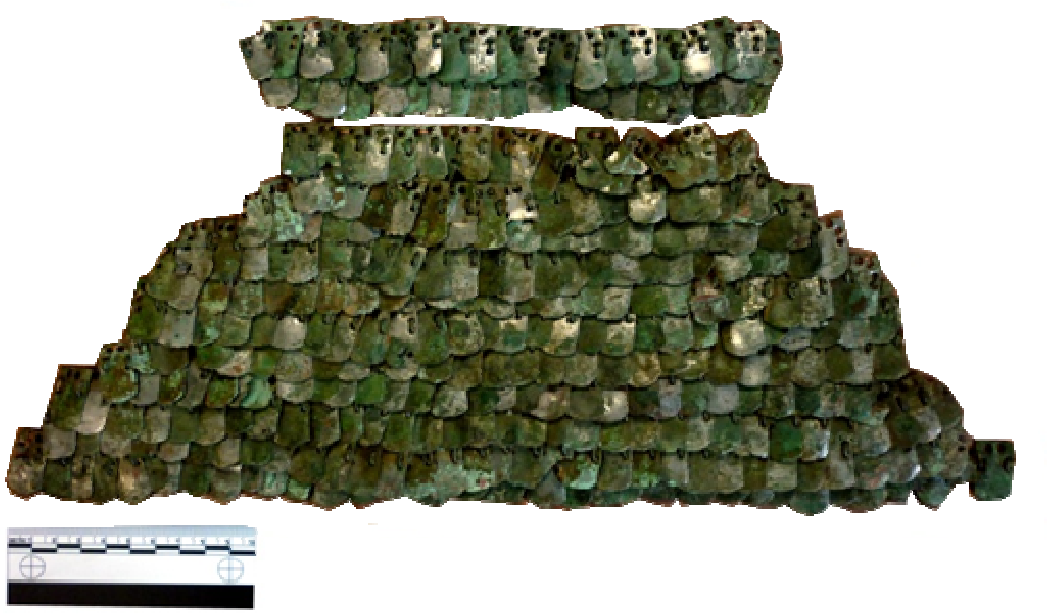


Figure 5.14 Large group of *lorica squamata* scales from Ham Hill on display at the Museum of Somerset in Taunton.

The scales were not analysed by AAS, but by EDS, because of their thinness (Table A4.2). Both tinned and un-tinned scales are made of brass (with 19.6% Zn). The tin plating can be clearly seen on a backscattered electron image (BEI) of an internal surface, and appears whiter than the bulk as tin has a higher atomic number than copper (Fig. 5.15). Tinning is only present on one side, and it remains only in certain areas of the scale.

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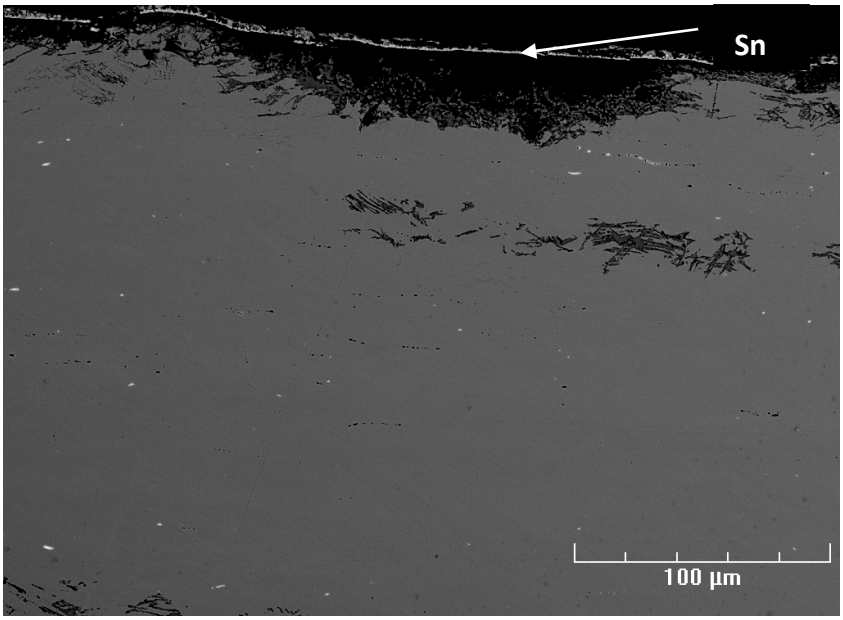

Figure 5.15 Backscattered electron image of brass scale A 1276 showing remaining tin plating.

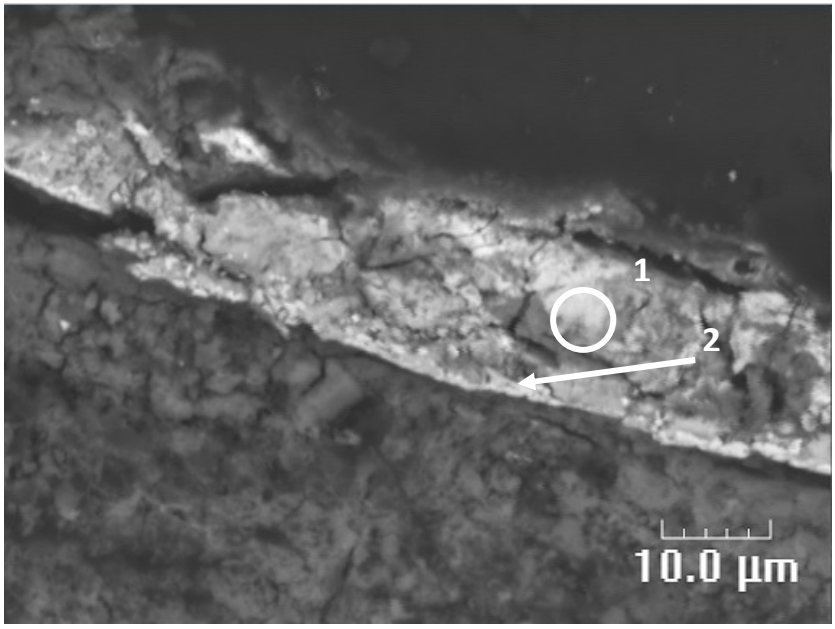

Figure 5.16 Ham Hill scale A 1276, Backscattered electron image with Analysis 1 (η phase) and 2 (ε phase) areas.

The tinning was analysed semi-quantitatively. No pure metallic tin remained from the original tin layer, but two layers of intermetallic copper-tin compounds. The presence and morphology of copper-tin compounds in tin-rich surfaces on copper alloy is diagnostic of the method of tinning (Meeks 1986). Two areas of the plating layer were analysed by EDS (Fig. 5.16). Analysis 1 was found to contain 63.8% tin, whereas the tin content for Analysis 2 was 55.8%. The composition for intermetallic compounds is fixed: 61% tin for eta (η), 38.2% for epsilon (ε), and 32.6% for delta

(δ). The layer at Analysis 1 is therefore very likely to be η, while that of Analysis 2 could be ε, the higher tin reading being due to the larger electron beam interaction width compared to the thickness of the layer of the second intermetallic compound.

Since compounds η and ε were found, and the morphology of η is not angular, it is very likely that the tinning was applied by hot wiping , and then heating at 250°C (Meeks 1986).

Gilded Roundel from Ham Hill (No accession number, Fig. A1.33)

This un-alloyed copper roundel bears stylistic resemblance to a flat copper-alloy disk with a central hole and decorated with niello from Neuss (Simpson 2000: 71) and is probably part of a horse harness. The roundel from Ham-Hill was examined under the SEM and a thin plating layer was found (Fig. 5.17). Upon EDS analysis the layer was found to be gold and the bulk, un-alloyed copper. The gold layer stands out very clearly when compared to the bulk of the material, which is surrounded by a thick layer of corrosion products that lie beneath the gilding and in some areas goes through the entire thickness of the sample.

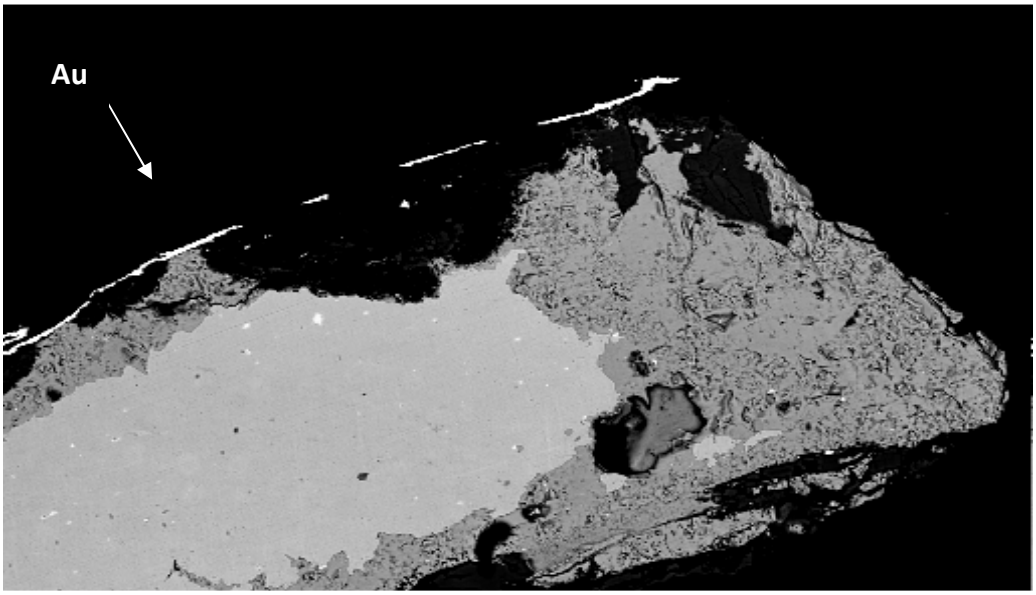

Figure 5.17 Backscattered electron image of the Ham Hill gilded roundel. A thin layer of gold can be seen at the top of the image, on a layer of corrosion products, and appearing whiter than any other feature.

Elements with higher atomic numbers appear whiter in backscattered electron images, but qualitative EDS analysis was performed to look for the presence of gold in the observed plating. While the spectrum confirmed the plating to be gold, there is no evidence for the presence of mercury, which would have been diagnostic of fire- or cold mercury gilding.

Fire gilding was the last gilding method to be developed, appearing after leaf- and foil gilding, and consists of applying a gold amalgam on a clean metal surface followed by heating to

evaporate the mercury. However a residual amount of mercury always remains and can be detected by several spectrographic methods. Conversely, cold gilding was described by Pliny as employing mercury only as an adhesive for gold leaf (Oddy 1993). Figure 5.18 shows spectra of the roundel gilding, and gold and mercury standard reference materials. It can be seen that the roundel gilding spectrum (blue) matches the position of the gold standard spectrum (green) for L peaks. This was not clear for M peaks (normally used for quantifying), due to overlapping.

Because mercury peaks are absent from the collected spectrum, this roundel appears to have been gilded by leaf-gilding, a mechanical process. This is consistent with the current view of the development of gilding techniques in Europe, as fire gilding does not appear to have been widely spread before the 2nd or 3rd century AD (Oddy op. cit).

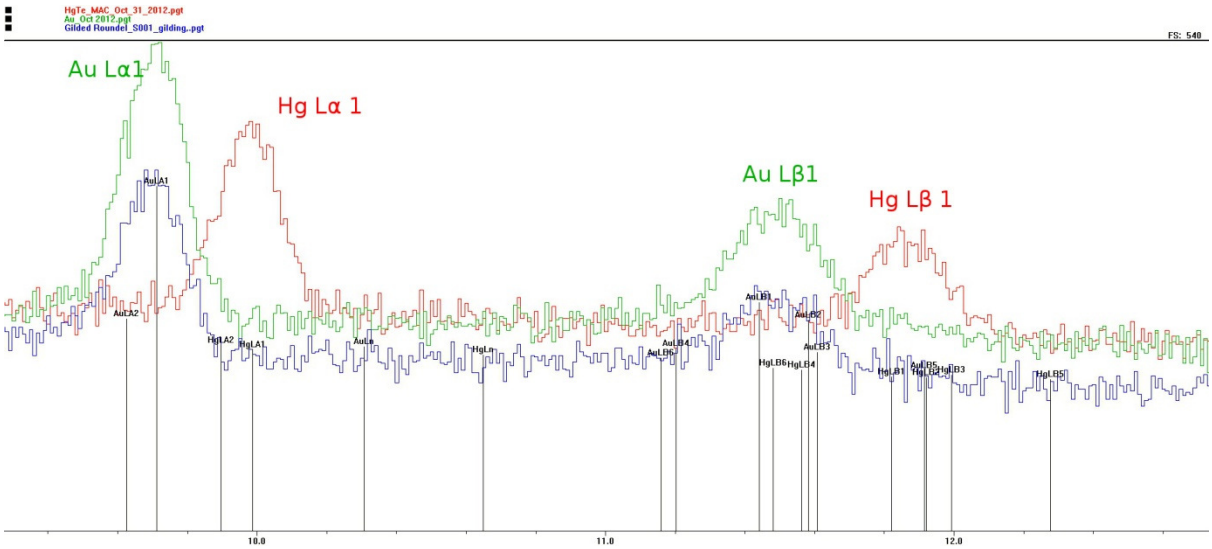

Figure 5.18 Section of between 9 and 13 keV for the acquired spectra of the gilded roundel (blue), and standard reference materials: mercury (red) and gold (green).

5.5 Carlisle

5.5.1 AAS results (Table A2.4)

5.5.1.1 Alloy type

Brass horse harness fittings, *lorica squamata* and *segmentata* constitute half of the assemblage analysed (Fig. 5.19). The distribution of the brasses is bimodal, with peaks at 22% and 18% signalling primary and secondary brasses, respectively (Fig. 5.20).

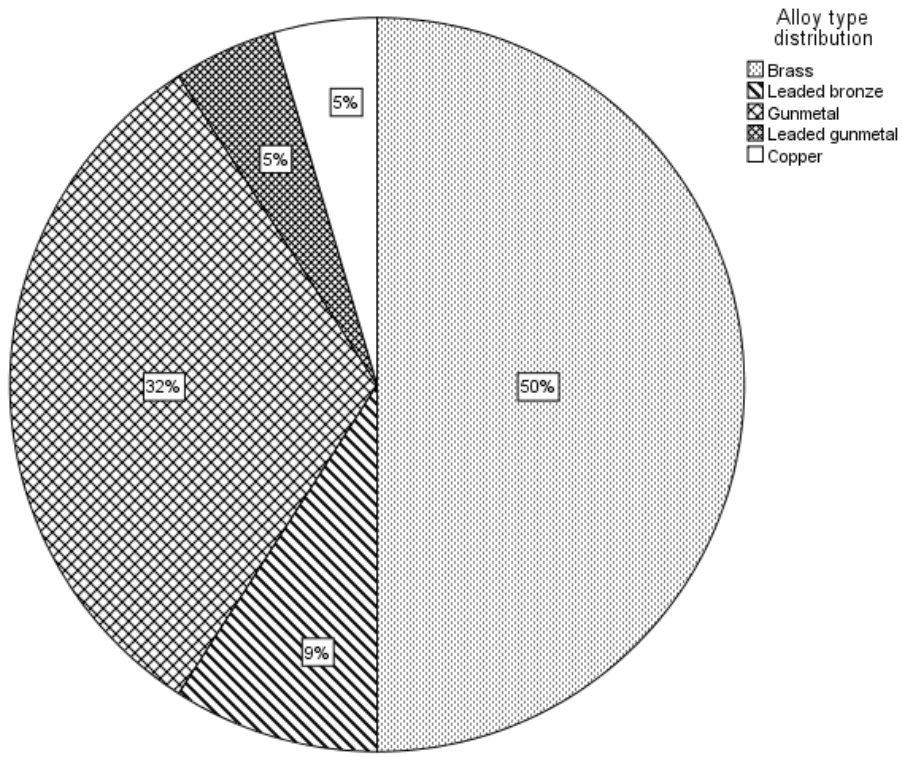

Figure 5.19 Alloy distribution for objects from Carlisle.

Gunmetals are second in frequency, and in objects such as scale armour and helmet fittings. There are only two bronzes, both leaded (a buckle plate and a strap end), and one unalloyed copper object (a cheek binding fragment).

Alloy Type	**Number of objects**	**%**
Copper	1	4.5
Leaded Copper	0	0
Brass	11	50
Leaded Brass	0	0
Bronze	0	0
Leaded Bronze	2	9.1
Gunmetal	7	31.8
Leaded Gunmetal	1	4.5
Total	22	

Table 5.1 Distribution of alloy type in the objects from Carlisle.

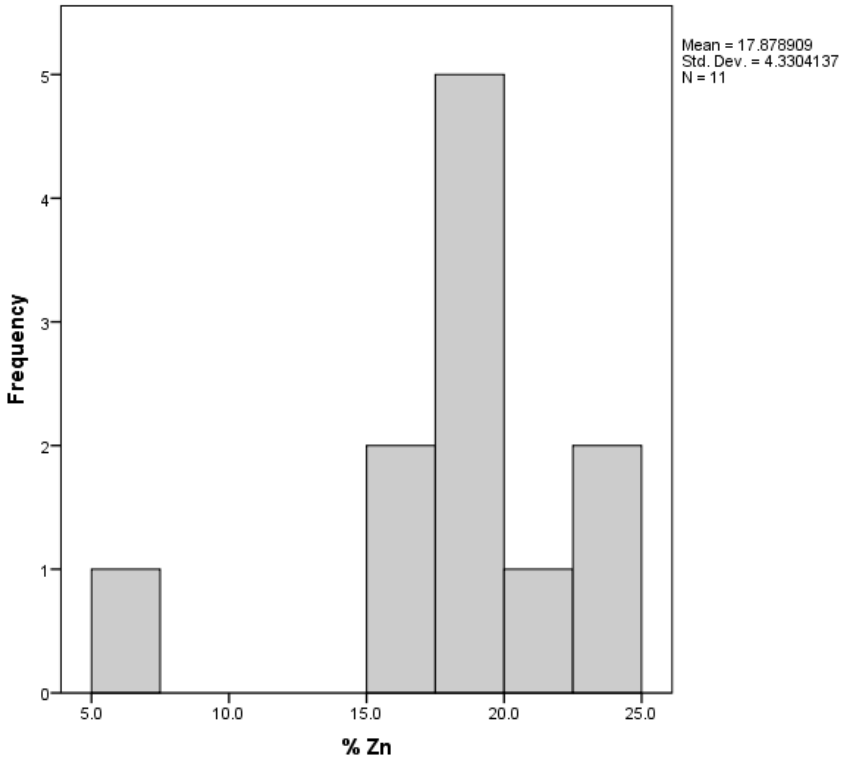

Figure 5.20 Zinc distribution in the brass objects from Carlisle.

5.5.1.2 Trace elements

When trace elements are considered in bivariate plots, a correlation and two groups are apparent. A nickel v. cobalt biplot suggests a correlation mostly of gunmetals from the same time period (Fig. 5.21-2). Figure 5.23 shows the correlation after removing outliers. An R^2 coefficient of 0.744 was obtained by linear regression, which means that 74% of the samples that appear on the graph are explained by the straight line shown: this indicates a strong correlation. Of the objects along this correlation, only one belongs to horse harness equipment, the rest being *lorica squamata*, shield binding and a cheekpiece protector.

When silver v. antimony (Figs. 5.24-5) and silver v. arsenic (Figs. 5.26-7) are plotted against each other no correlation can be seen for either pair of elements, but two groups of objects defined by levels of arsenic and antimony form. In Figure 5.24-5 all the labelled dots but one, belong to horse harness fittings and the same dots correspond to the upper cluster in Figures 5.26-7, which correspond to the silver v. arsenic plots. Since these elements are associated with the copper, the group differences might reflect a different source for copper for cavalry units.

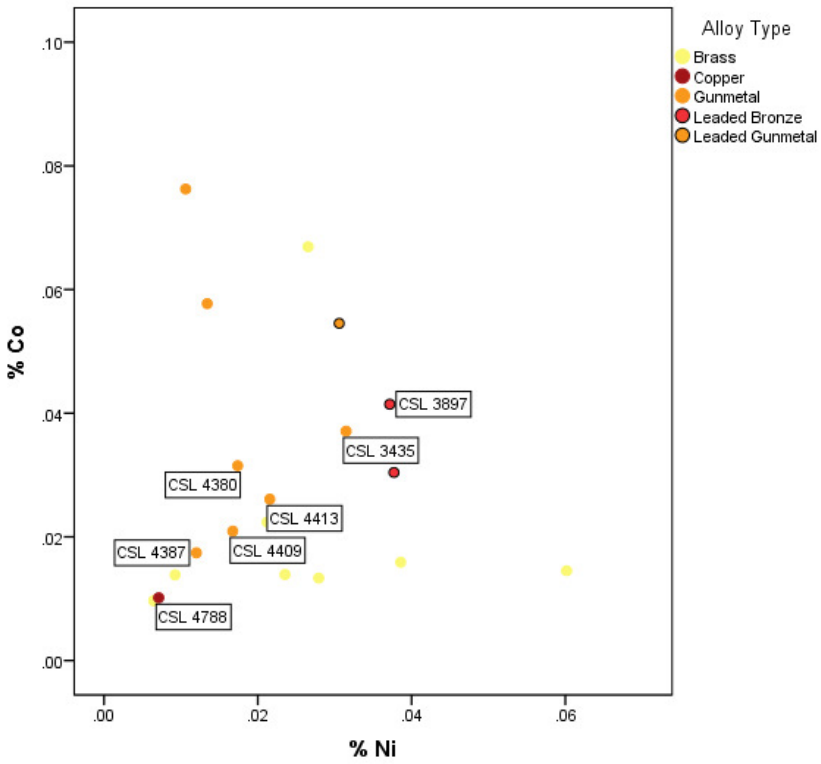

Figure 5.21 Carlisle. Nickel v. cobalt bivariate plot, with both elements re-scaled to the copper, by alloy type

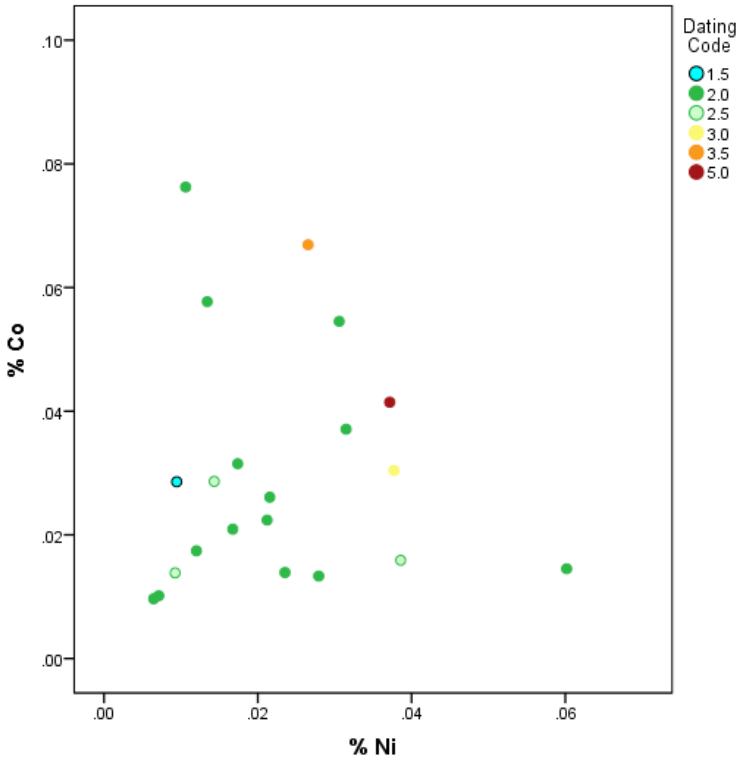

Figure 5.22 Carlisle. Nickel v. cobalt bivariate plot, with both elements re-scaled to the copper, by time period.

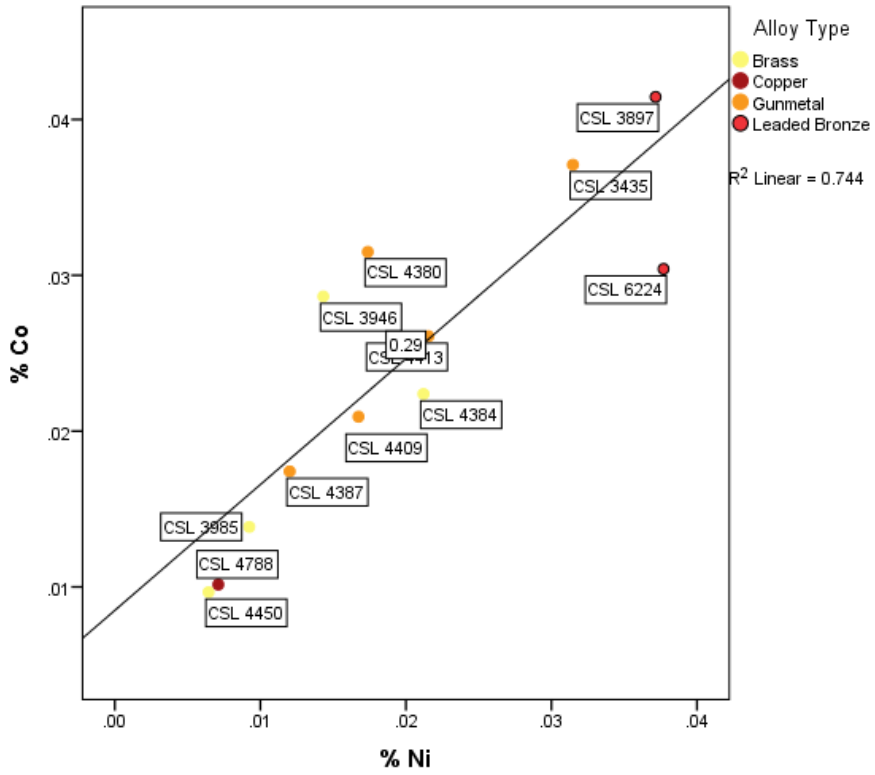

Figure 5.23 Correlation between nickel and cobalt of some samples from Carlisle.

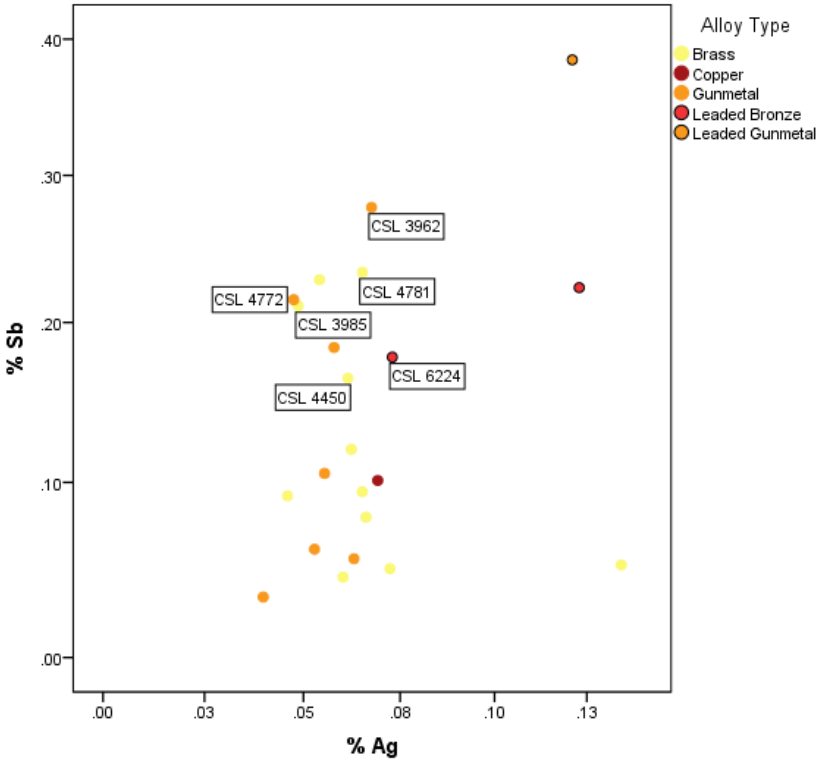

Figure 5.24 Carlisle. Silver v. antimony bivariate plot, with both elements re-scaled to the copper, by alloy type.

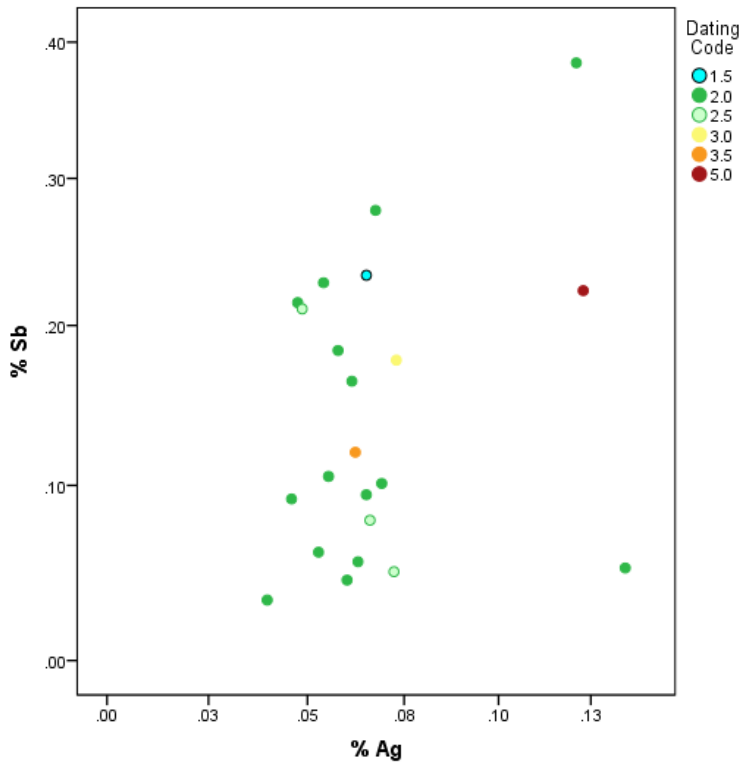

Figure 5.25 Carlisle. Silver v. antimony bivariate plot, with both elements re-scaled to the copper, by time period.

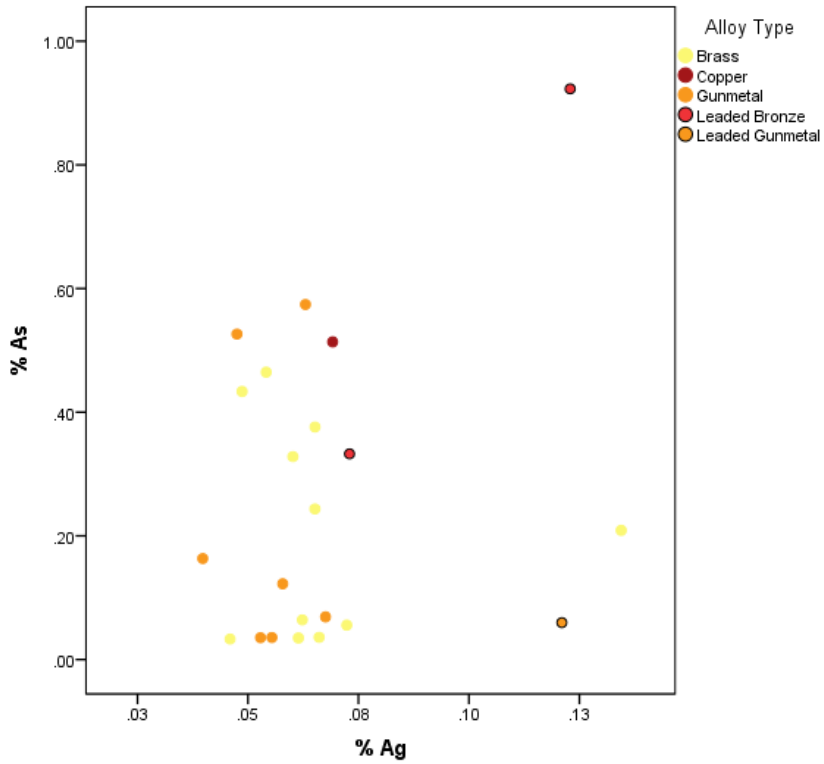

Figure 5.26 Carlisle. Silver v. arsenic bivariate plot, with both elements re-scaled to the copper, by alloy type.

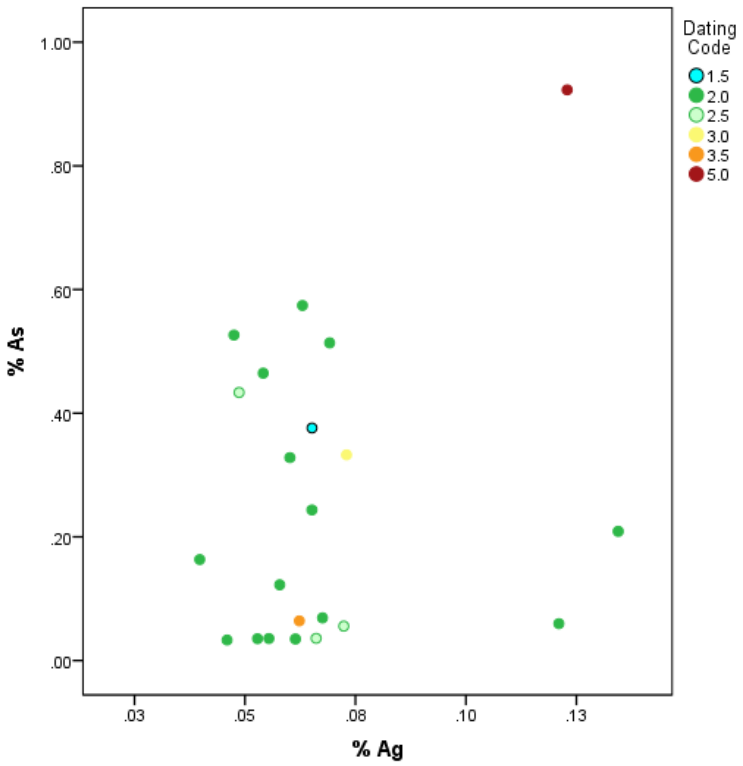

Figure 5.27 Carlisle. Silver v. arsenic bivariate plot, with both elements re-scaled to the copper, by time period.

5.5.2 Metallography

Eight objects from Carlisle were analysed by metallography. Two of them, a horse harness pendant, CSL 2788 (Fig. 5.28), and a buckle plate, CSL 6224 (Fig. 5.29) show a dendritic structure, indicating casting as the method of manufacture. In the case of the pendant the structure was cold worked after casting, as evidenced by generalised strain lines and moderately deformed dendrites.

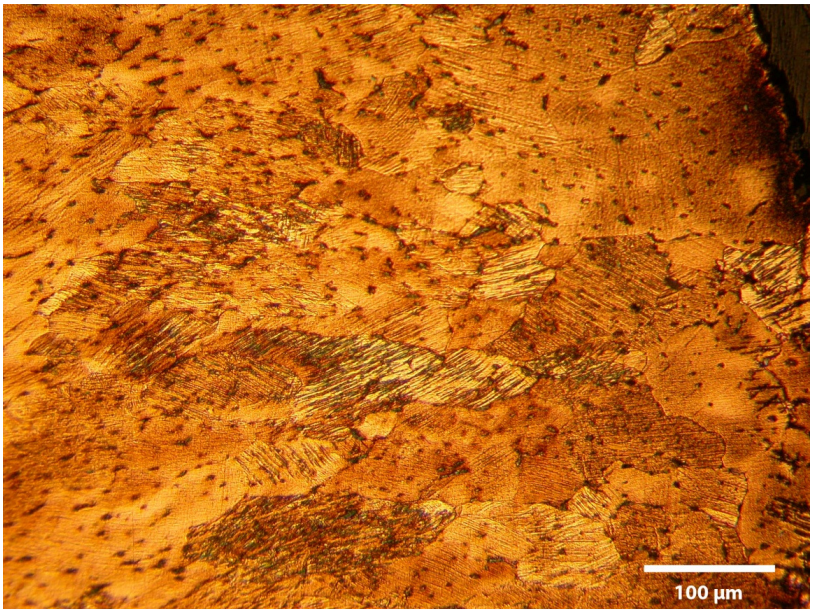

Figure 5.28 CSL2788.

The buckle plate, CSL 6224, in Figure A3.25 shows only slight deformation. It presents a very small amount of a second phase in addition to the copper-tin α phase, the eutectoid δ phase, since it contains 7.8% tin. This is a non-equilibrium phase at room temperature, but the full- equilibrium phase, ε, would not be obtained at this level of tin without annealing the alloy for thousands of hours (Scott 2011). In the realistic copper-tin phase diagram, the δ phase starts to appear at about 10% tin. However, it can be seen at lower tin levels if the alloy solidified faster, as the tin composition and the presence of a second phase suggest (see dashed line in Fig. 5.30).

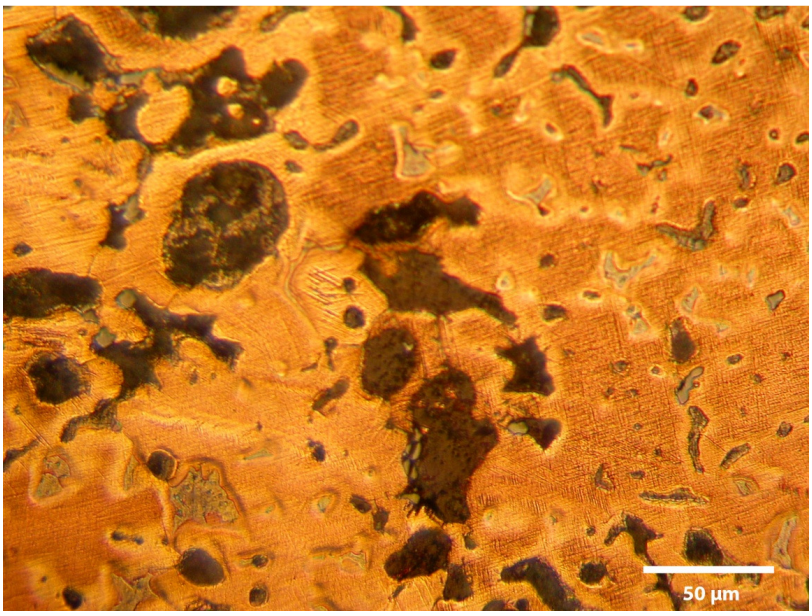

Figure 5.29 CSL6224.

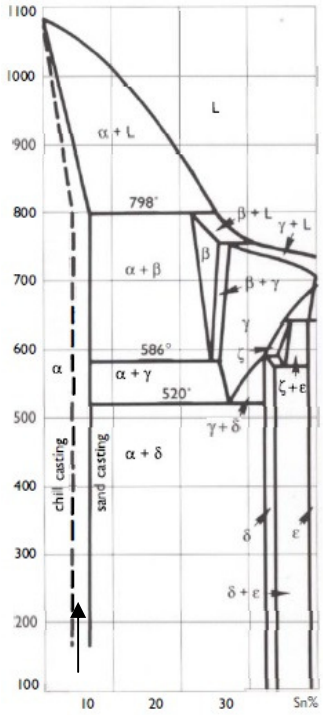

Figure 5.30 Copper tin phase diagram relevant to ancient bronzes showing the difference in composition for the appearance of phase η at low temperatures, after Scott (1991).

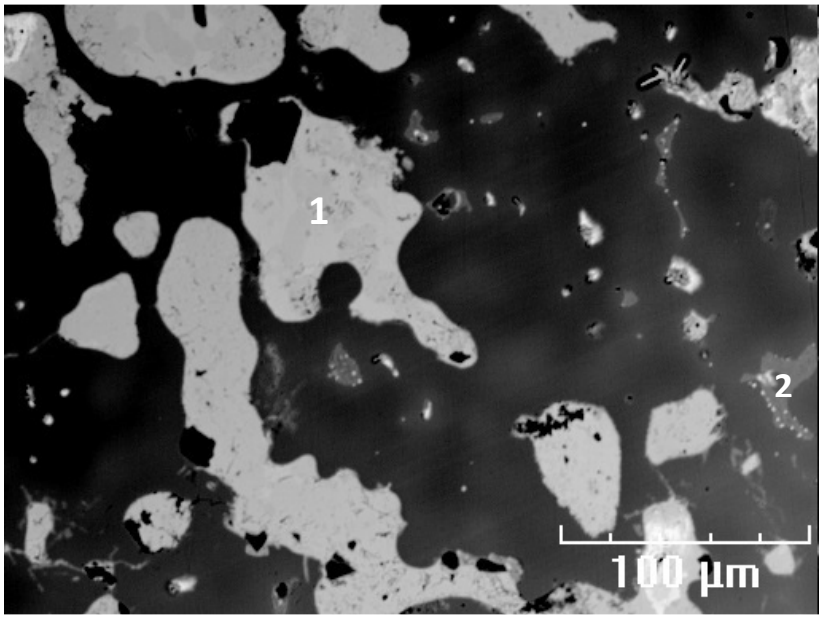

Figure 5.31 Backscattered electron image of CSL6224. Area 1: Lead. Area 2: Cu-Sn α+δ phase. The darker background is the solid solution α phase.

Two areas of CSL6224 were analysed by EDS (Fig. 5.31) and it was found that Area 1 is lead, and the slightly darker Area 2 the Cu-Sn α+ δ eutectoid phase, as it was found to contain 32.2% Sn. The theoretical value for δ in this phase is 32.6% (Meeks 1986).

CSL2043 (Fig. 5.32) and CSL3985 (Fig. 5.33) are both horse harness strap junctions, and present a very similar microstructure in terms of grain size. The grains for CSL3985 are slightly more deformed and show more strain lines. Both microstructures present twinning and reveal cycles of working and annealing.

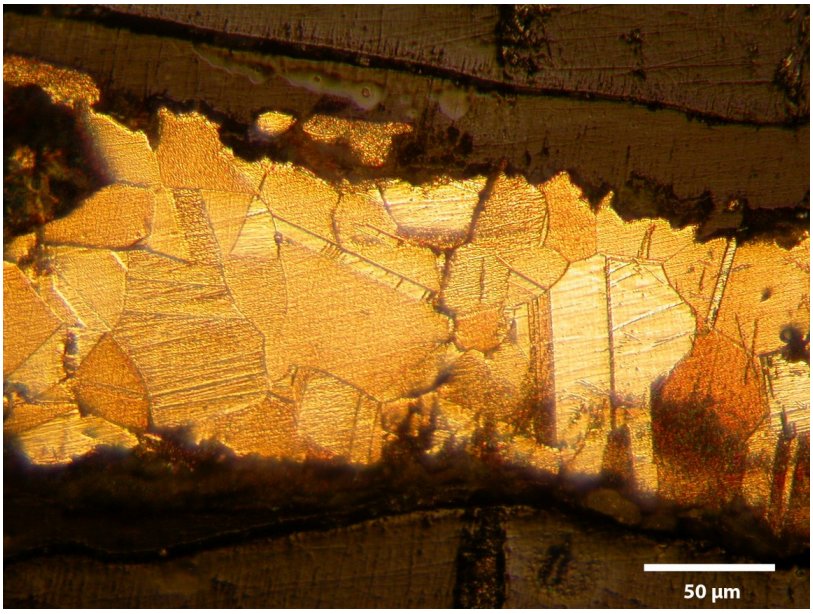

Figure 5.32 CSL2043.

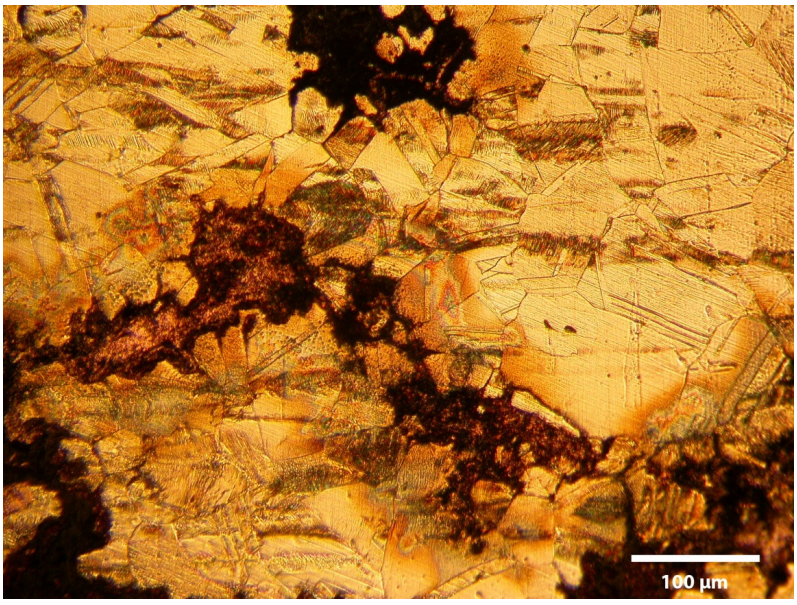

Figure 5.33 CSL3985.

CSL2042 is the same type of object as CSL2043. However, the microstructure is different. CSL2042 still shows the remnants of the original dendritic cast structure (Fig. 5.34). However, twinning can be seen in the sample, which is indicative of cold working and reheating. The object could have been cold worked after being cast, and reheated after for a short period of time, or at a temperature below recrystallization for a cast structure; the areas with a higher amount of cold work could have recrystallised first, and the object was completed before the rest of the dendritic structure recrystallised.

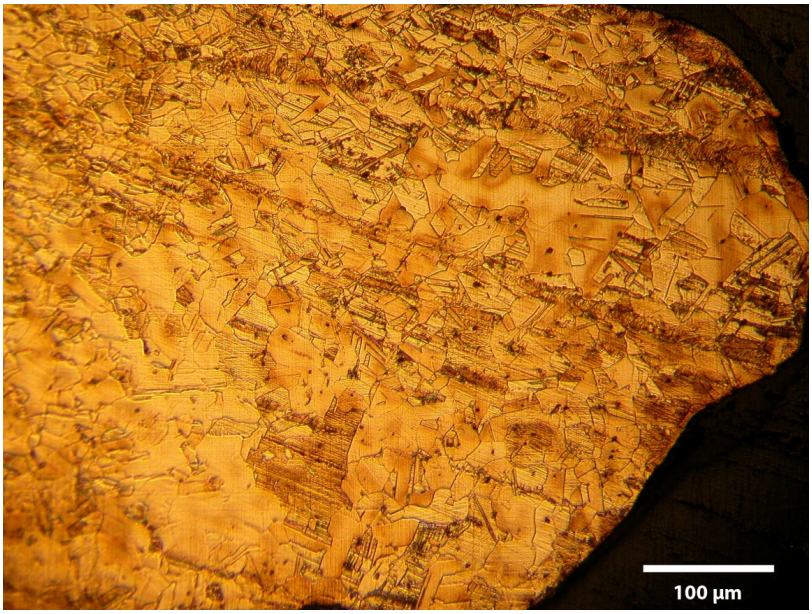

Figure 5.34 CSL2042.

In the case of the *lorica squamata* scale, CSL 3946 (Fig. 5.35) and the saddle plate CSL4772 (Fig. 5.36) grains are smaller and reveal a longer history of cold-working and annealing cycles. This situation is extreme in the case of cheek binding CSL4788 (Fig. 5.37), which was subjected to extreme cold working in the last stage of its production. The grains are very small (around 4µm), and most have been so heavily deformed that they appear as bands.

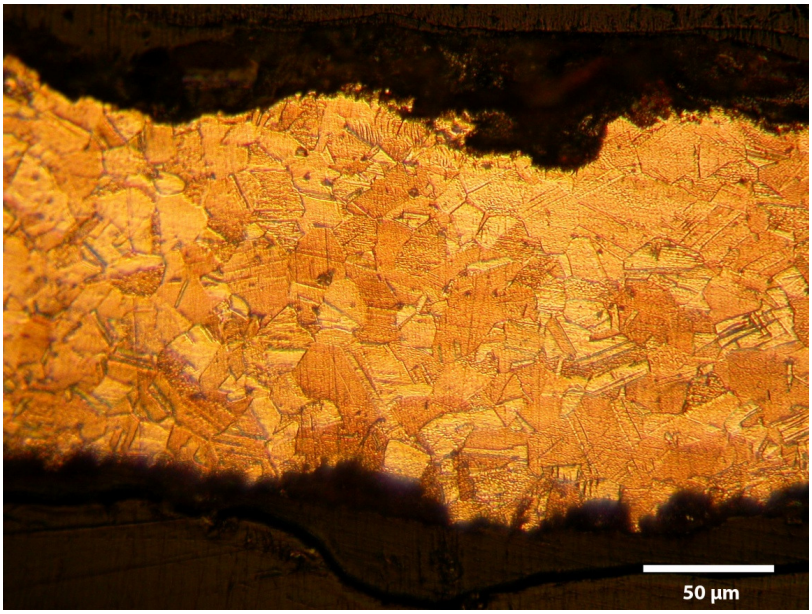

Figure 5.35 CSL3946.

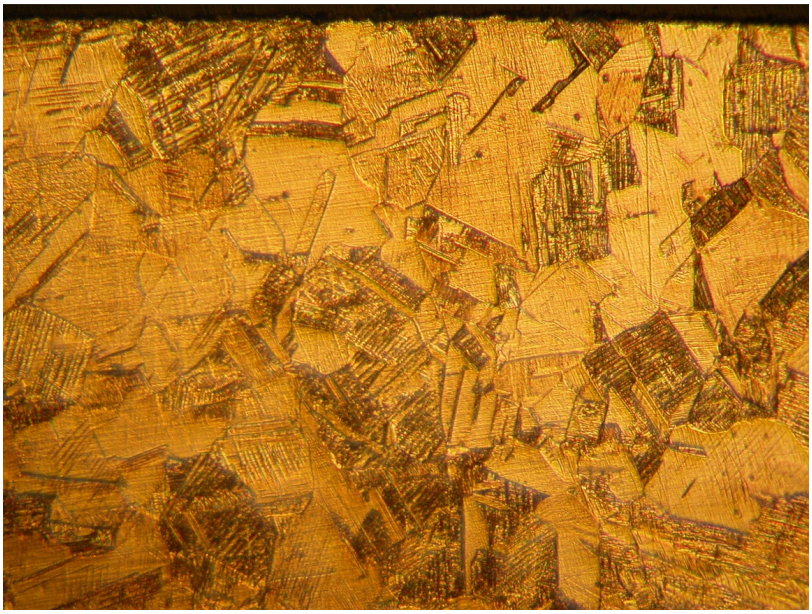

Figure 5.36 CSL4772.

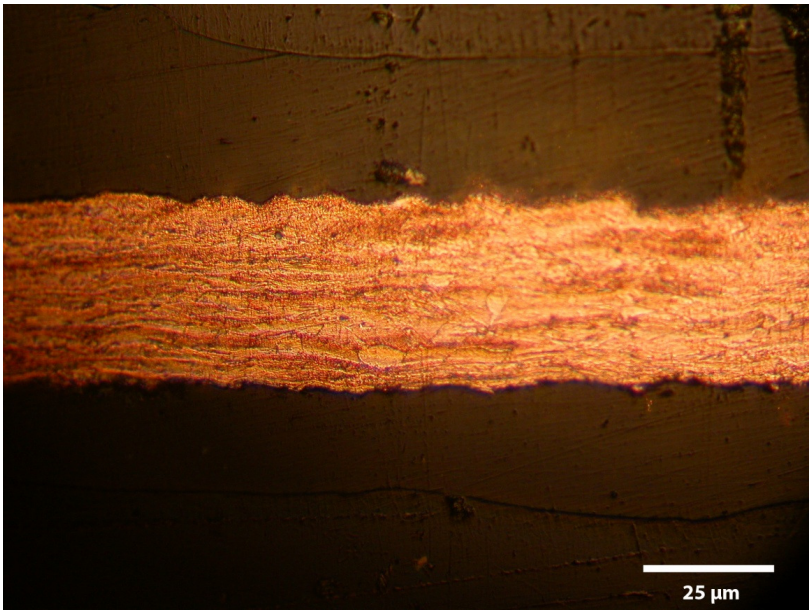

Figure 5.37 CSL4788.

5.6 Usk

5.6.1 AAS results (Table A2.2)

5.6.1.1 Alloy type

The seven objects sampled belong to three different alloys. A *lorica segmentata* lobate hinge and a belt buckle are made of brass, a *lorica segmentata* hinged buckle and a horse harness junction loop are made of gunmetal and there are three bronzes (all leaded): a scabbard slide, a buckle tongue and a harness ring.

5.6.1.2 Trace elements

Of the seven objects from Usk, four are of pre-Flavian date, and the remaining objects belong to third century contexts. This sample size and configuration is not sufficient to establish tendencies by trace elements considering this site alone, and the objects from Usk are best put in perspective when considering objects from other sites.

5.6.2 Metallography

The *lorica segmentata* lobate hinge USKManF3N7 (Fig. 5.38) a granular structure can be seen, which is characteristic of materials with a long history of cycles of annealing and cold working: twinning, strain lines distributed in several grains across the surface of the cross section, and small grain size (approx. 9µm). In addition it shows a transgranular fracture that runs longitudinally to the cross-section of the sample, due probably to stress-corrosion cracking. This could have been a post-

depositional fracture, residual stresses from the manufacturing process and the corrosive environment playing a dual role.

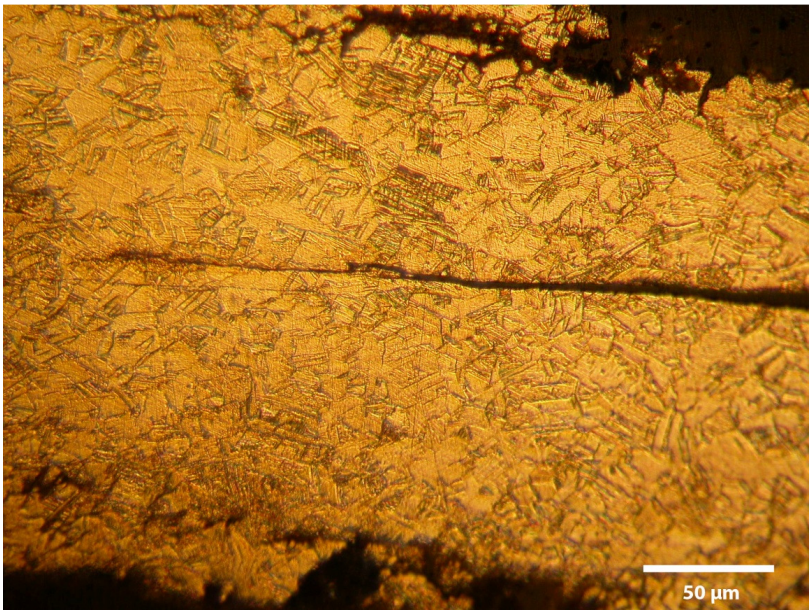

Figure 5.38 USKManF3N7.

The hinged buckle from a *lorica segmentata,* USKManF4N8 (Fig. 5.39), shows grains with similar size and shape. Although it is a gunmetal containing 4.6% tin, this quantity is not enough to form a second phase in the alloy. This object, however, seems to have been silvered, as very small traces of silver (Fig. 5.40) were found where the buckle was examined with SEM-EDS, as the corresponding peak in the EDS spectrum indicates (Fig. 5.41).

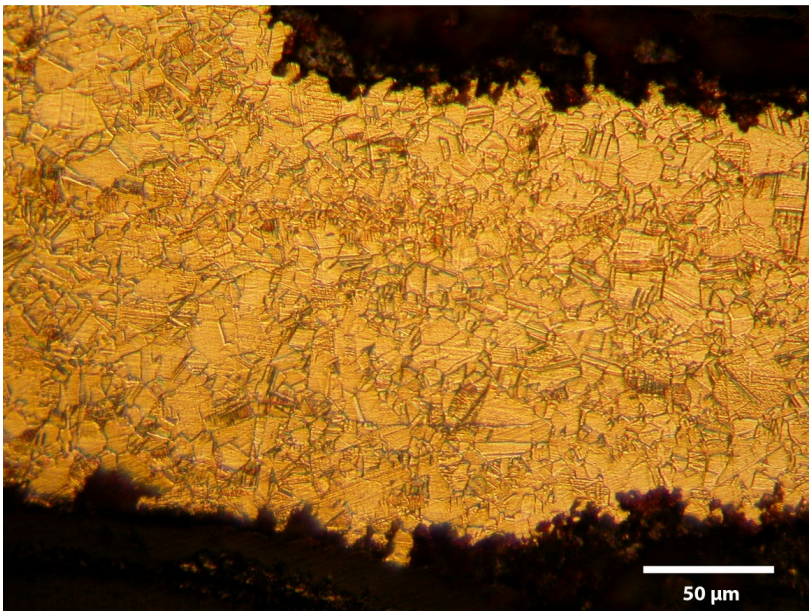

Figure 5.39 USKManF4N8.

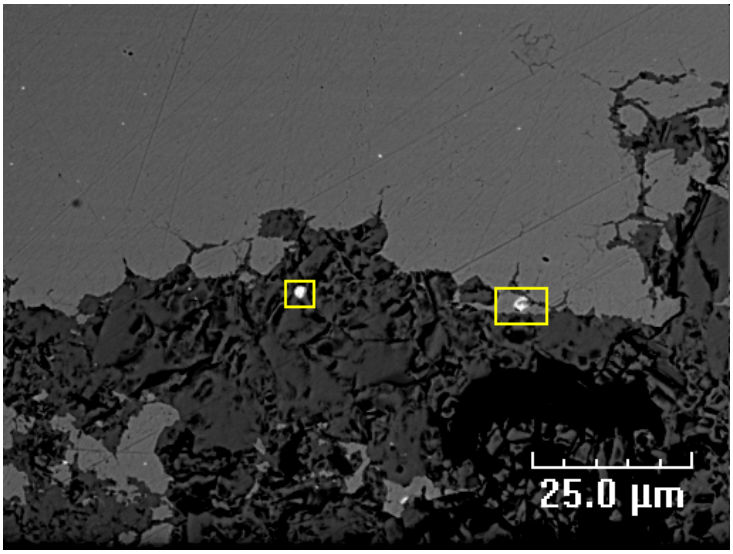

Figure 5.40 USKManF4N8 White spots inside the yellow boxes were analysed and found to be silver.

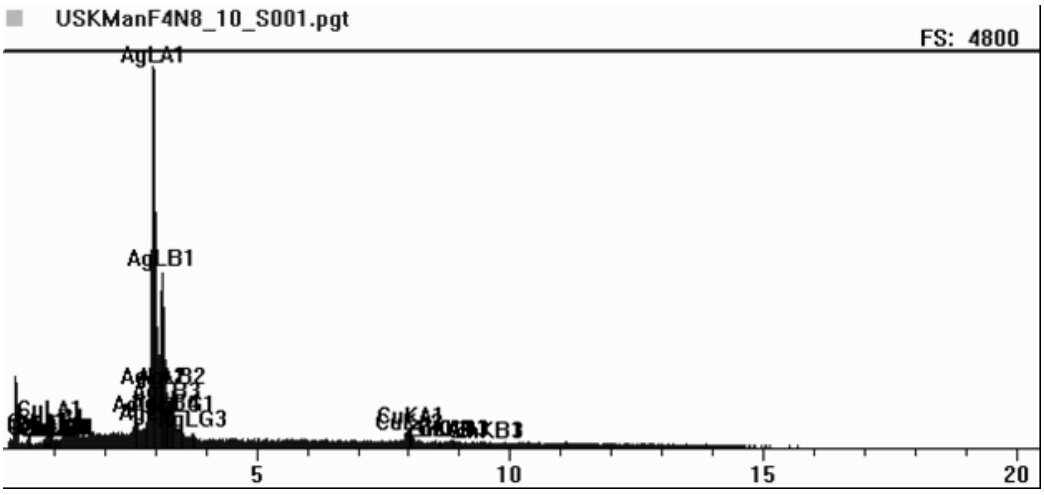

Figure 5.41 EDS spectrum for one of the areas analysed in USKManF4N8, showing pure silver (Ag).

A horse harness junction loop made of gunmetal, USKManP40N3 (Fig. 5.42) shows a dendritic structure, in which the outer crystals have been very heavily deformed by cold work in the last manufacturing process. Evenly distributed lead globules can be seen across the inner surface, but are aligned in the direction of the deformation in the areas close to the edge (Fig. 5.43).

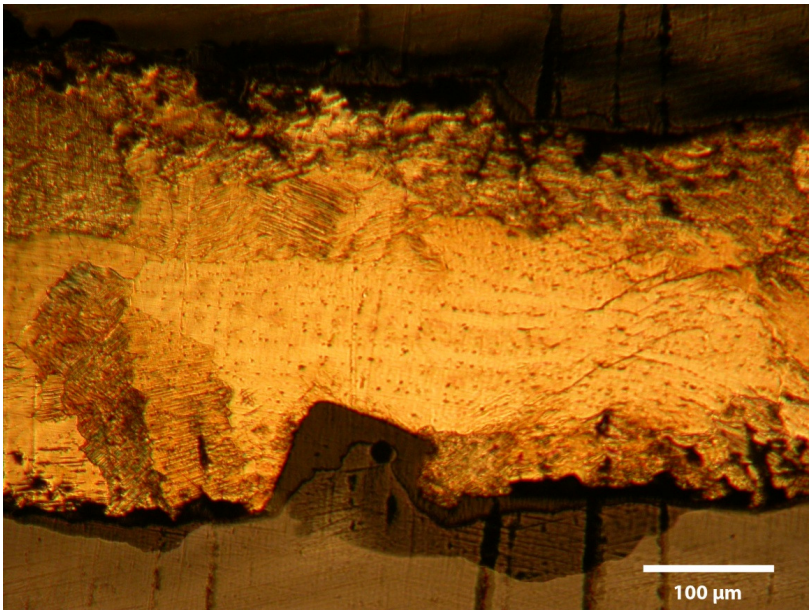

Figure 5.42 USKManP40N3.

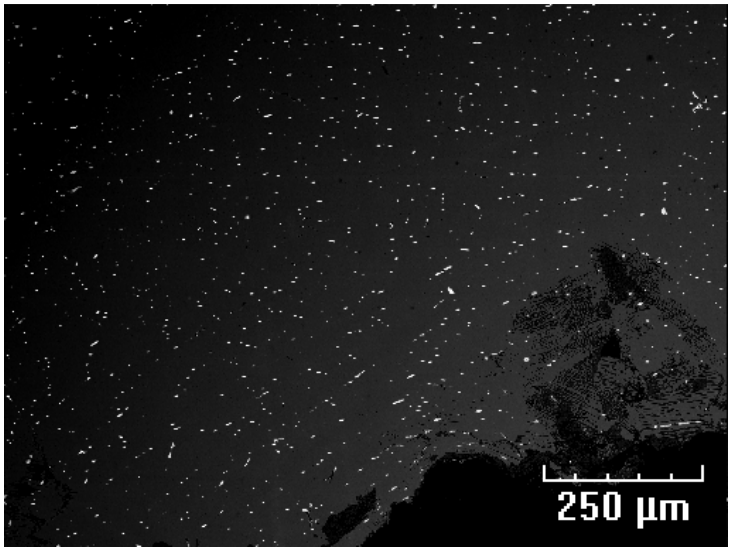

Figure 5.43 Backscattered electron image of USKManP40N3, showing the distribution of lead globules.

Another cast object is the harness ring USKManP40N8 (Fig. 5.44), which presents an as-cast dendritic structure. The object contains 12.3% tin, which is enough to form a second phase. However it is not clearly seen under optical microscopy (Fig. 5.45), since the interdendritic space is also occupied by oxidised lead (3% of the total composition). Further observation under backscattered electron mode (Fig. 5.46) reveals the presence of the α+ δ eutectoid phase which can be seen in blue in Figure 5.47.

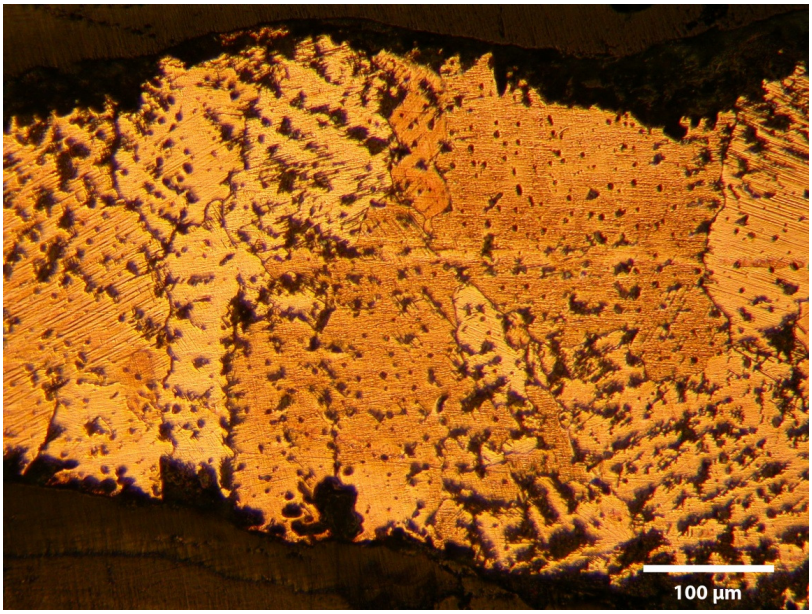

Figure 5.44 USKManP40N8.

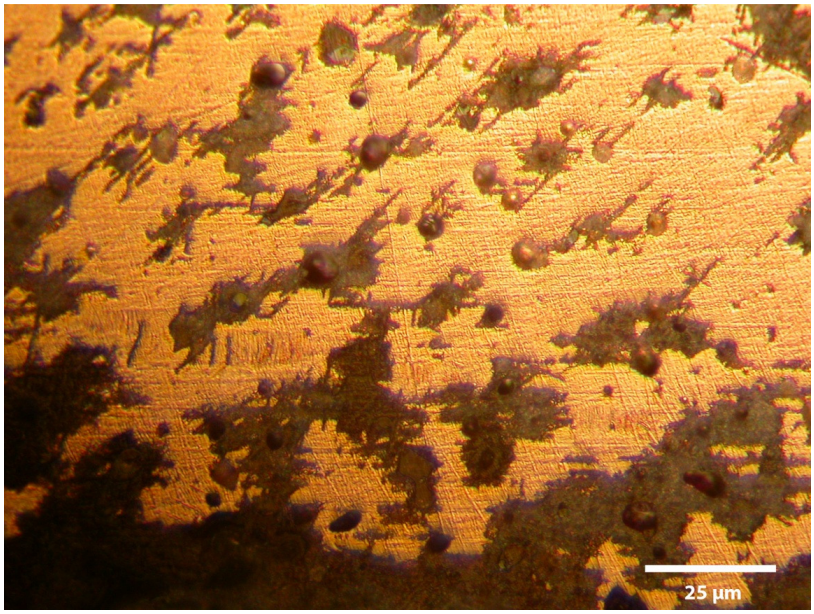

Figure 5.45 USKManP40N8.

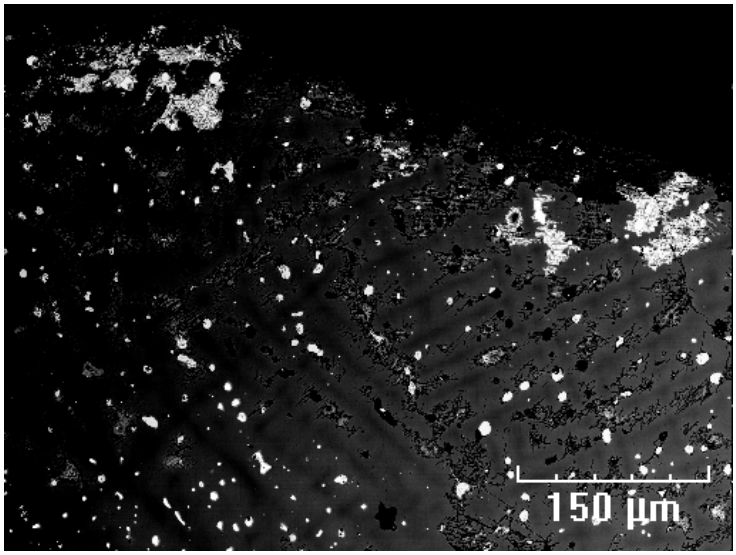

Figure 5.46 Backscattered electron image of USKManP40N3, showing lead in white, and the δ phase in light gray.

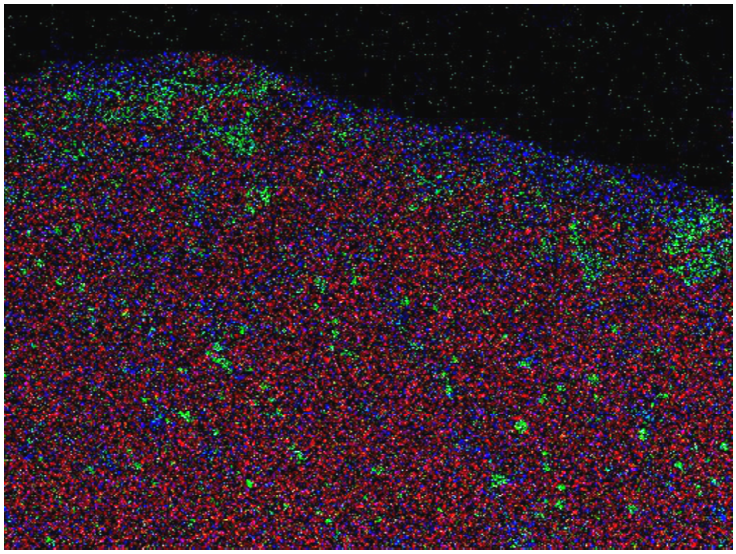

Figure 5.47 Elemental mapping micrograph, showing copper in red, lead in green and tin in blue. Blue areas correspond to the α+δ phase.

5.7 Chester

5.7.1 AAS results (Table A2.5)

5.7.1.1 Alloy type

Taking into account all the objects analysed by AAS, the assemblage is dominated by bronzes, which represent nearly half of the total (44%), and all but one are leaded (Fig. 5.48). The rest of the assemblage is divided evenly between brasses (26%) and gunmetals (29%). However, if

only the objects from the first two centuries AD are considered (Fig. 5.49), the proportion of brasses then increases at the expense of the leaded bronzes: 48% brass, 24% bronze (19% leaded) and 29% gunmetal. As with the material from Carlisle, the objects from Chester belong to different periods, although those from the late 1st century and early 2nd constitute the majority.

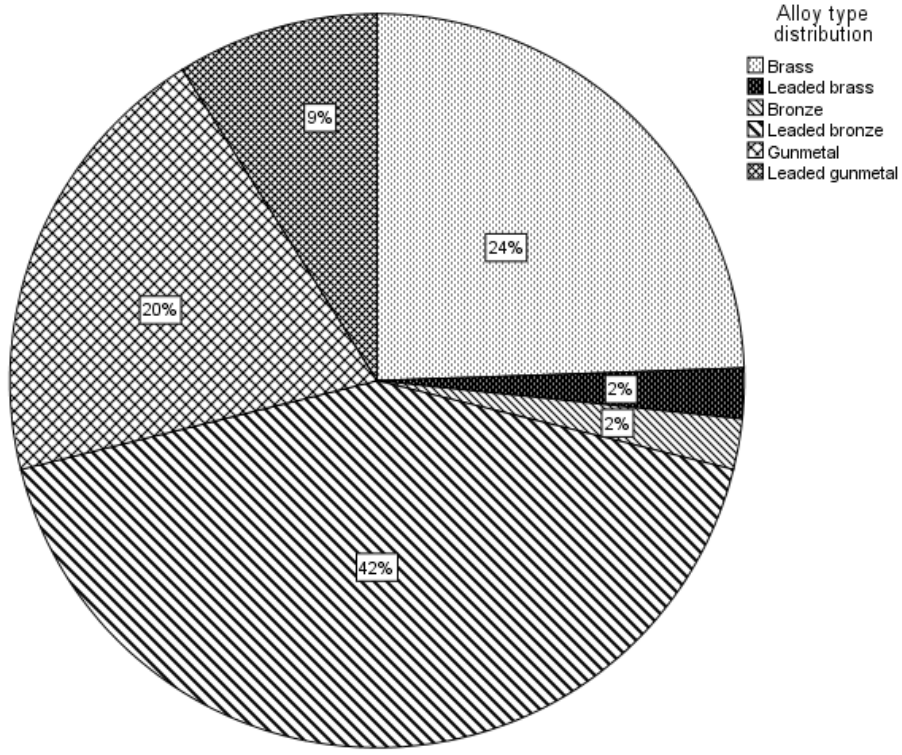

Figure 5.48 Distribution of alloy type in the objects from Chester.

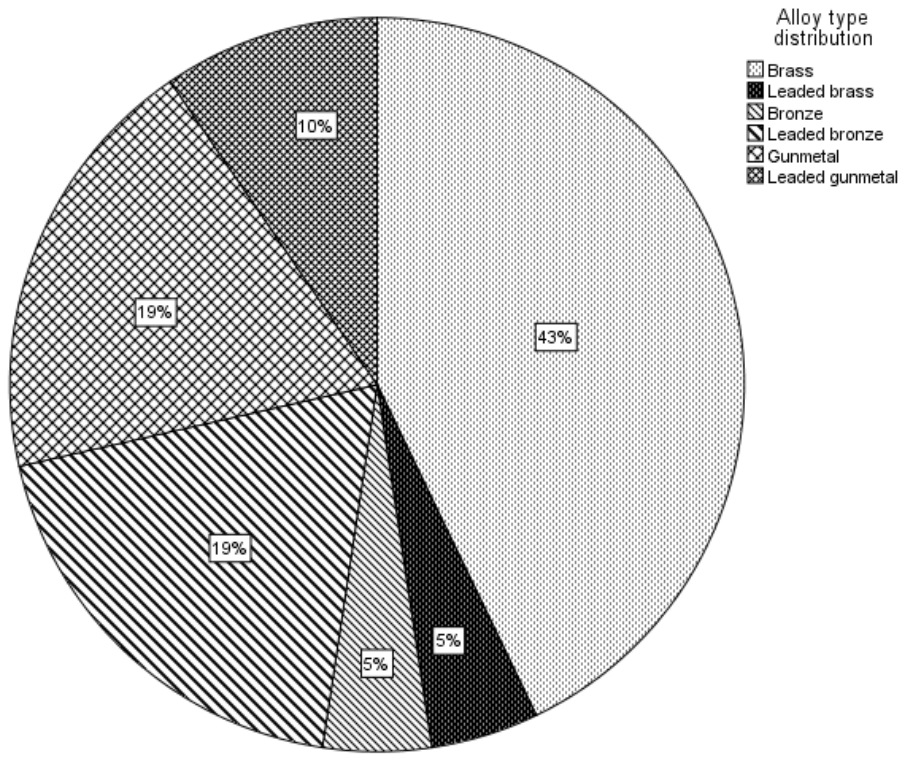

Figure 5.49 Distribution of alloy type in the objects from Chester from the 1st and 2nd centuries AD.

When zinc is plotted against tin (Fig. 5.50) an inverse correlation accounting for 72% of all the samples can be seen. In addition, the plot shows that the tin content gradually increases with time at the expense of the zinc, especially after the second century (colour code above 3). Another observable feature is that in later periods, bronzes with little zinc (at trace levels) become common.

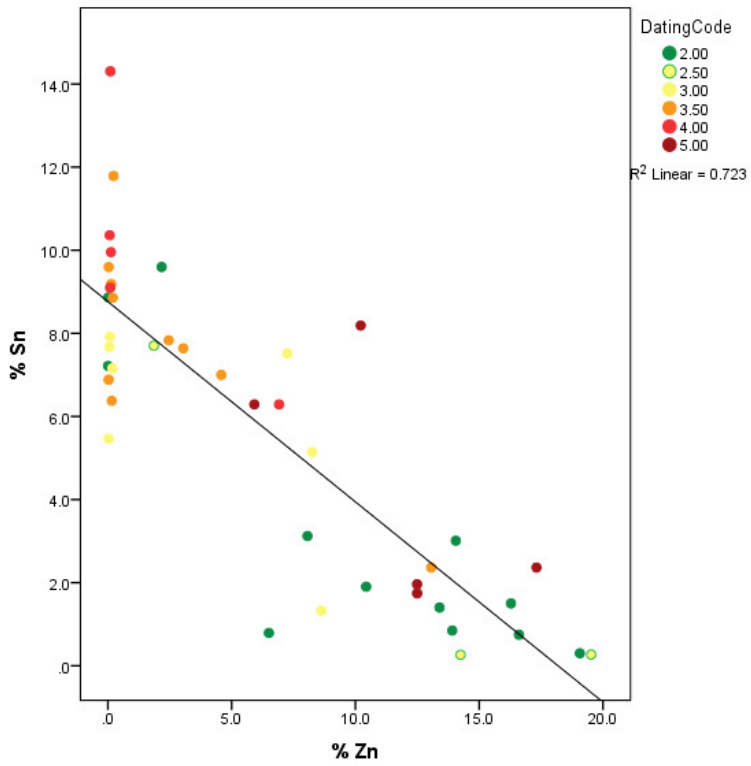

Figure 5.50 Chester. Zinc v.tin plot by time period, revealing a typical negative correlation.

5.7.1.2 Trace elements

Lead and antimony are not correlated either by alloy type or time period (Figs. 5.51-2). It can be assumed then that the antimony in the samples is related to the copper and so the antimony can be re-scaled to it. It can be seen from Figure 5.52 that leaded alloys tend to belong to later periods, mainly after the second century (colour code above 3).

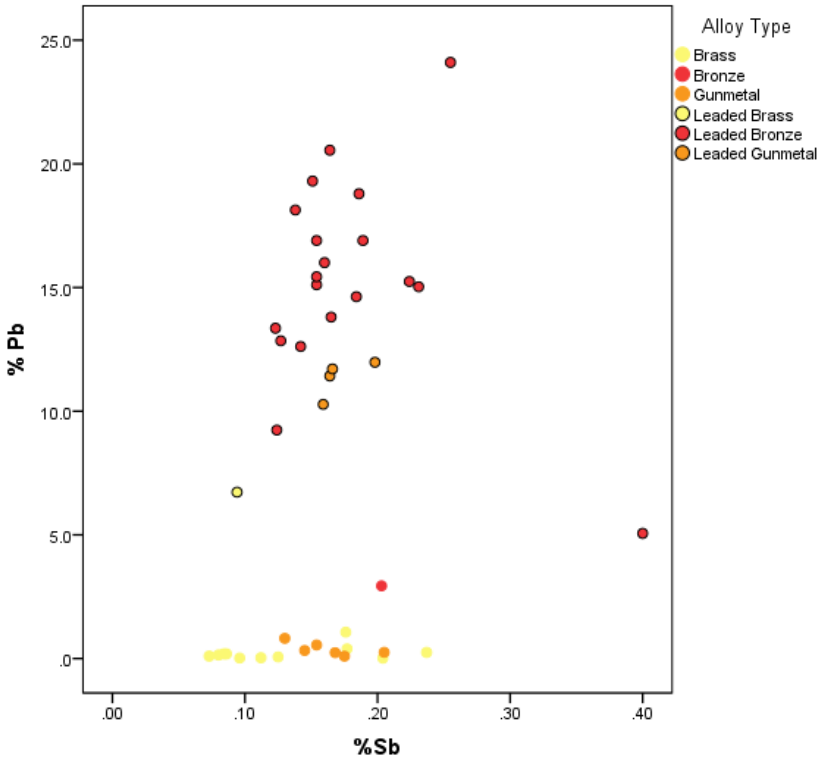

Figure 5.51 Chester. Antimony v. lead bivariate plot (by alloy type) showing no correlation.

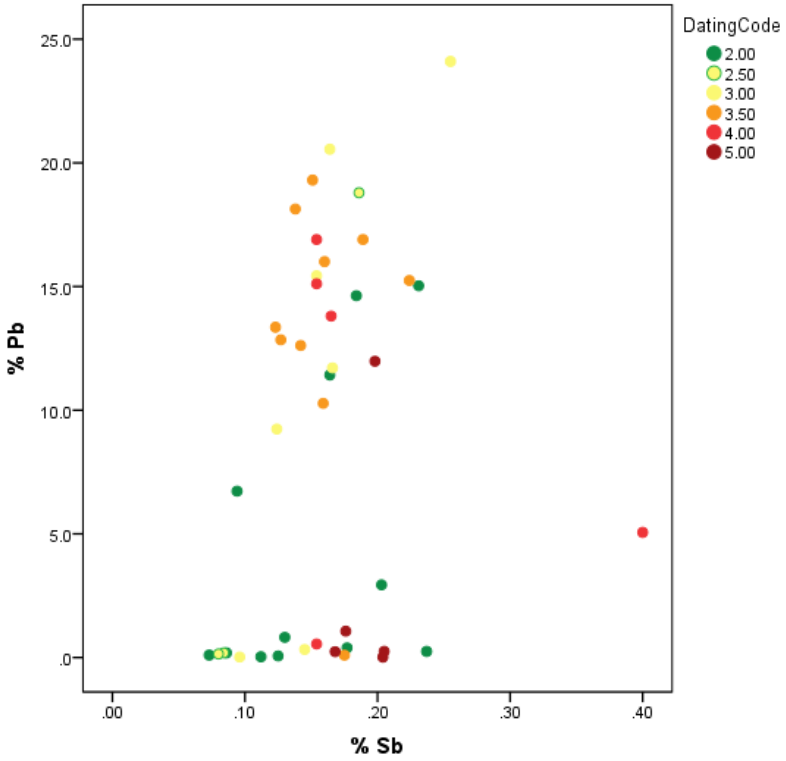

Figure 5.52 Chester. Antimony v. lead bivariate plot (by time period) showing no correlation.

In a bivariate plot of nickel against antimony (Fig. 5.53) a separation defined by alloy type can be seen, with brass objects having a lower nickel content. Two leaded groups can be seen, one formed by gunmetals and bronzes, and a second group comprising bronzes, the latter with a higher nickel content. The higher nickel leaded bronze group is composed mainly by Newstead type *lorica segmentata* fittings, horse harness fittings, and plates. Samples from the same high nickel content group tend to belong to later periods of time (Fig. 5.54).The leaded bronzes also contain higher levels of silver, which can be seen in Figures 5.55 and 5.56, where silver against arsenic and silver against nickel plots are presented. When plotting silver and nickel together (Fig. 5.56-7) there is no clear correlation between them.

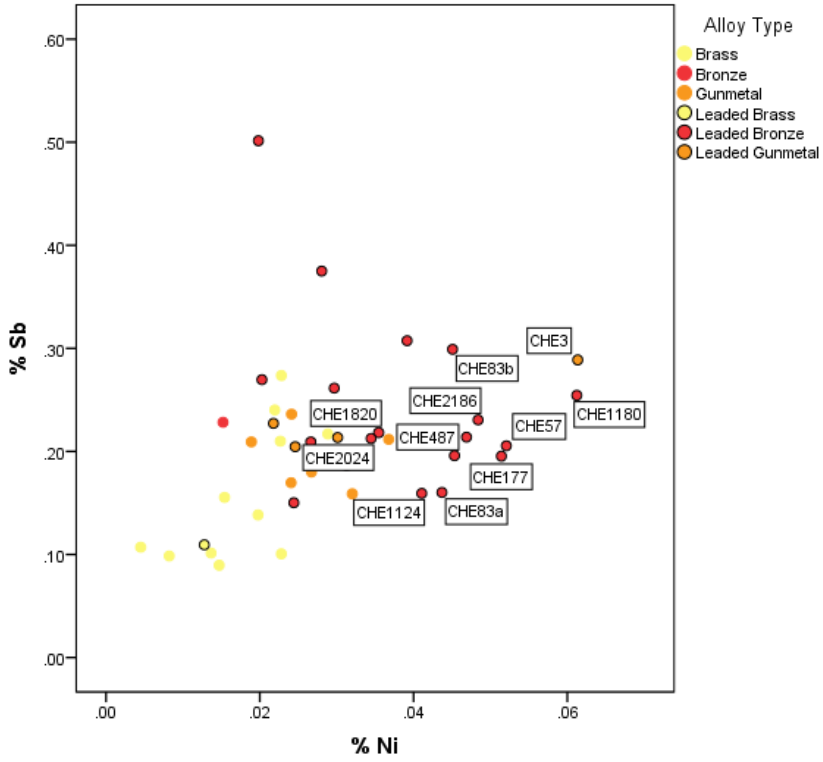

Figure 5.53 Chester. Nickel v. antimony bivariate plot, by alloy type. Sample name labels are shown for higher nickel leaded bronzes. Both elements were re-scaled to the copper.

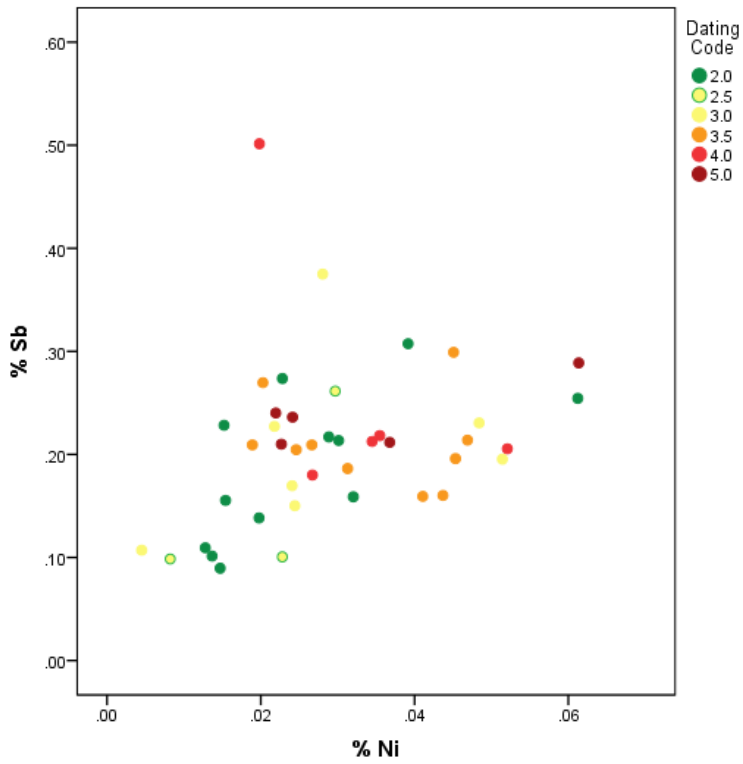

Figure 5.44 Chester. Nickel v. antimony bivariate plot, by time period. Both elements were re-scaled to the copper.

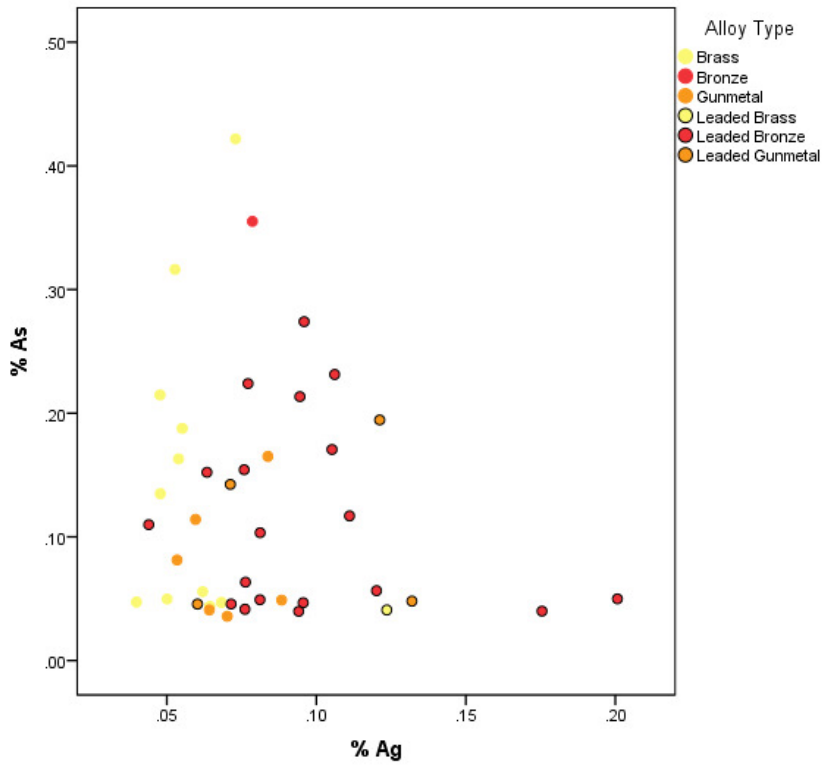

Figure 5.55 Chester. Silver v. arsenic bivariate plot, by alloy type. Both elements were re-scaled to the copper.

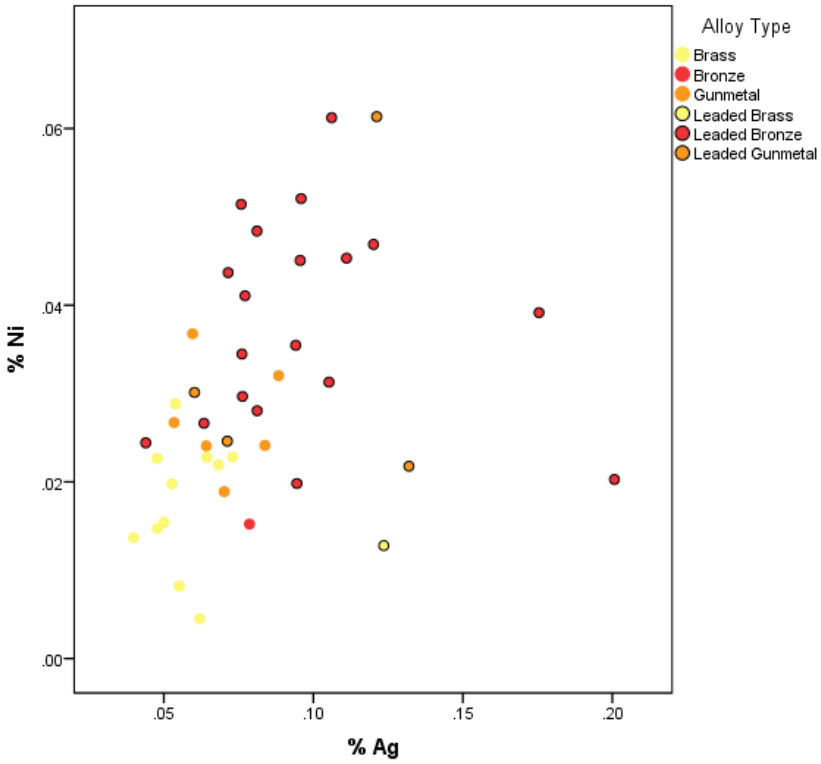

Figure 5.56 Chester. Silver v. nickel bivariate plot, by alloy type. Both elements were re-scaled to the copper.

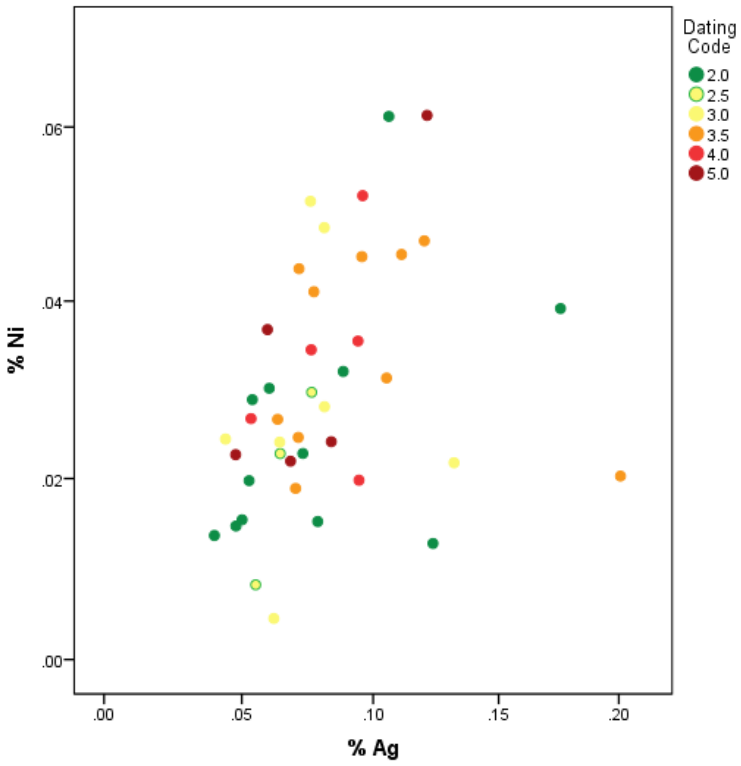

Figure 5.57 Chester. Silver v. nickel bivariate plot, by time period. Both elements were re-scaled to the copper.

5.7.2 Metallography

A gunmetal pendant, CHE3 (Fig. A3.37-8), shows a dual phase structure of slightly deformed dendrites. Lead and the α+δ-phase can be seen filling the space between dendrite arms, as both lead and the α+δ-phase solidify last upon cooling after casting. The lead surface is oxidised and appears dark, but the α+δ phase can be seen as light-grey (Fig. A3.38). Under the SEM, both the lead and the α+δ phase are clearer (Fig. 5.58).

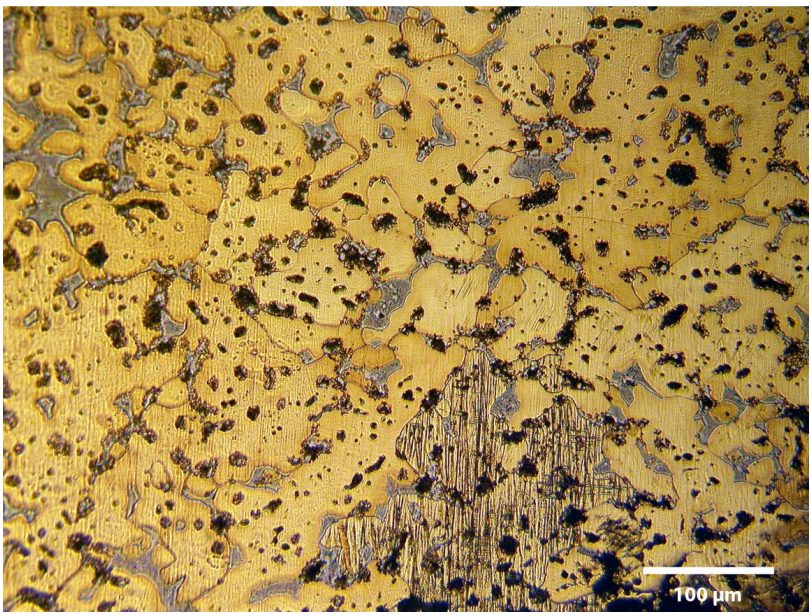

Figure 5.58 CHE3.

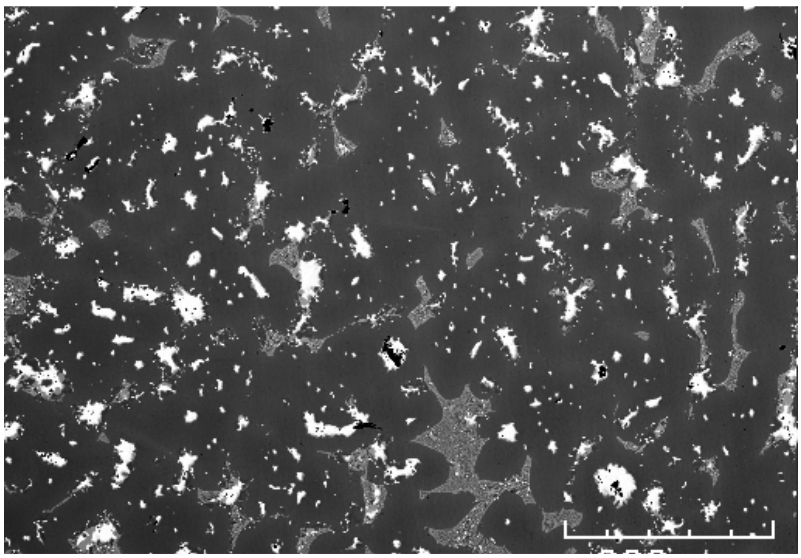

Figure 5.59 SEM backscattered electron image of pendant CHE3 showing lead in white and α+δ phase in light grey.

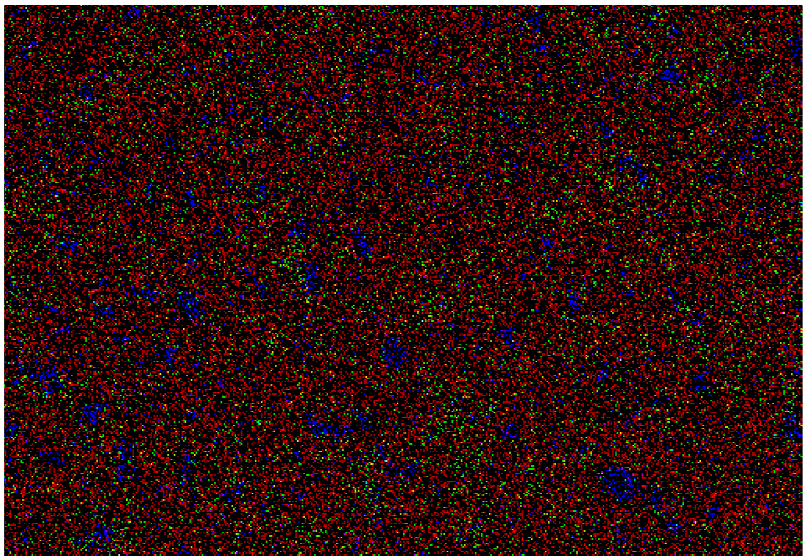

Figure 5.60 SEM image of pendant CHE3 and elemental mapping showing copper (red), tin (green), and lead (blue), with green corresponding to the α+δ phase.

CHE21 (Fig. 5.61) is a brass dagger chape with small grain size, twinned grains and generalised strain lines, evidencing cycles of cold working and reheating. It is extensively corroded, this being better appreciated with backscattered electrons under the SEM, where the structure can be seen in the un-etched condition due to intergranular corrosion (Fig. 5.62).

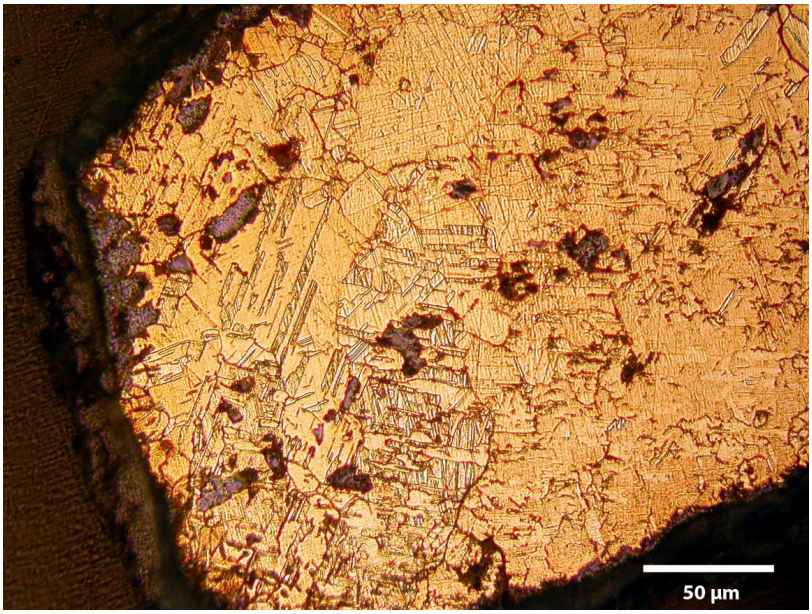

Figure 5.61 CHE21.

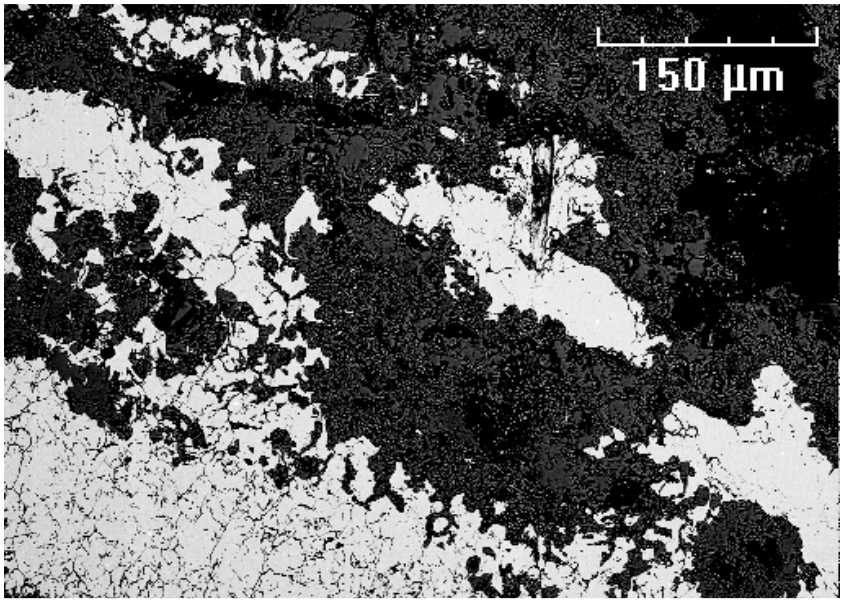

Figure 5.62 Backscattered electron image of dagger chape CHE21, showing extensive corroded areas and intergranular corrosion.

A rectangular plate, CHE57 (Fig. 5.63) is a leaded cast bronze containing 9.1% tin, and shows a similar microstructure to CHE21, with deformed dendrites and showing α+δ phases and islands of lead distributed across the surface of the sample.

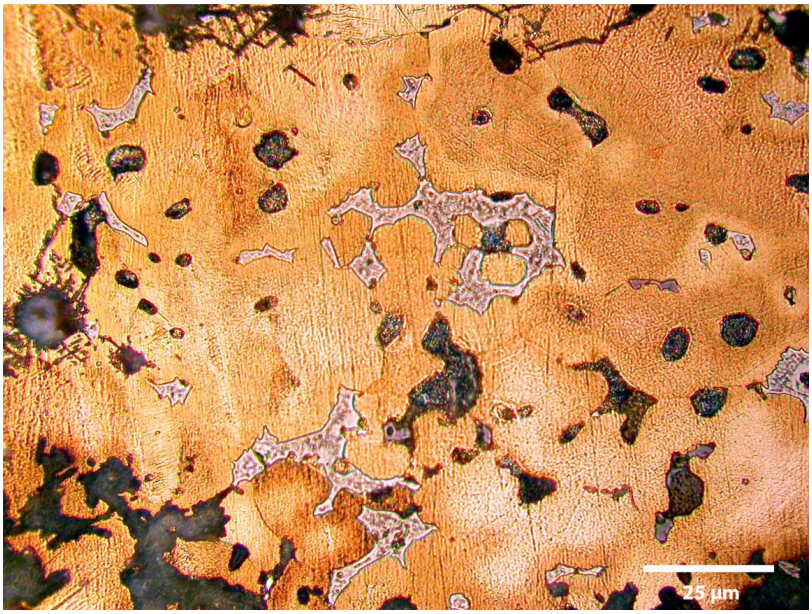

Figure 5.63 CHE57.

A gunmetal armour scale, CHE142 (Fig. 5.64) and a brass rectangular plate CHE261 (Fig. 5.65) show a granular structure with twins, moderate deformation and generalised strain lines. CHE142 has lead stringers showing the direction of deformation through its fabrication history. However, the main difference between them is grain size, with the rectangular plate having grains three times as large as those of the *lorica* scale.

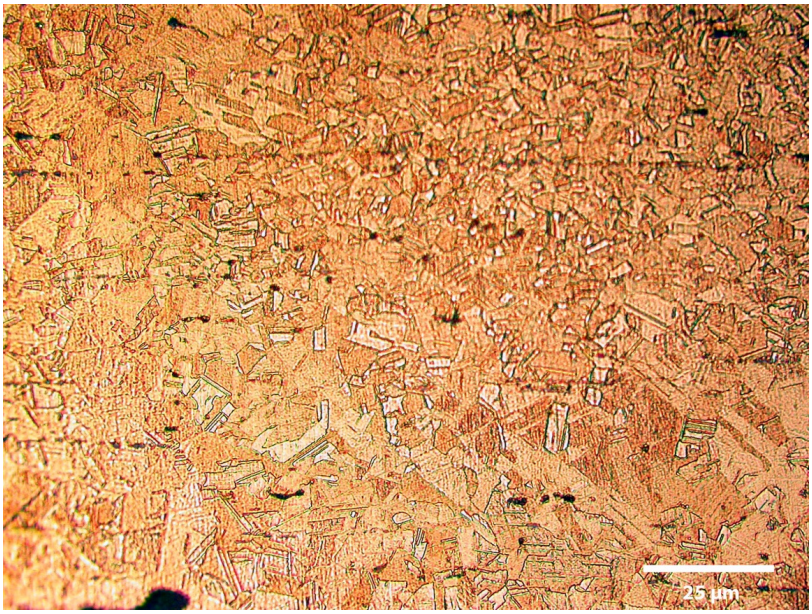

Figure 5.64 CHE142.

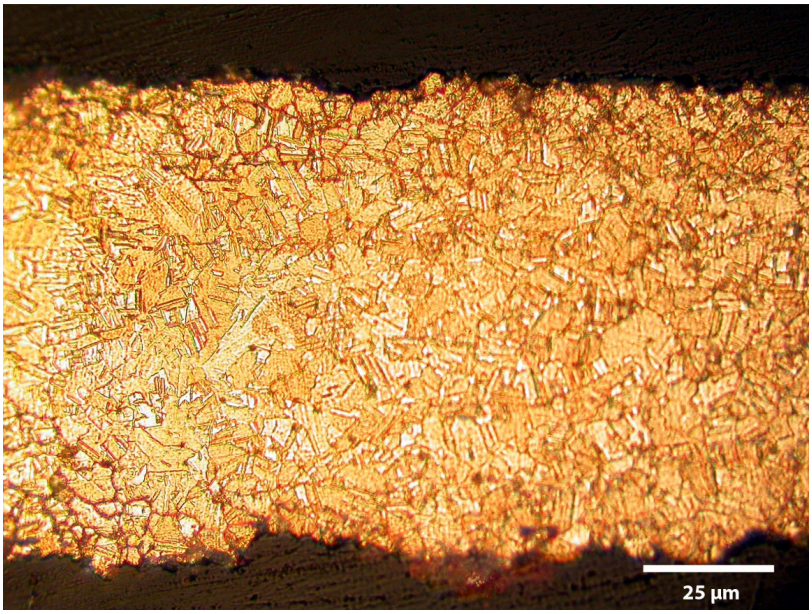

Figure 5.65 CHE261.

CHE349 (Fig. 5.66), CHE701 (Fig. 5.67) and CHE848 (Fig. 5.69) are *lorica segmentata* fittings made of metal sheet. The first two are two brass buckles and the third a gunmetal *tie* with less than 3% tin, which is not enough to generate a second phase in the microstructure. The buckles have microstructures very similar in shape, but differ in grain size (16 and 28µm). The *lorica* tie, however, is heavily deformed and has two areas of different grain sizes, the smallest being 11.5µm. This means that the area with the smallest grains underwent a further reduction in thickness. The sample was taken from the upper tip shown at Figure A1.83. Considering the tapering shape of the object at

the tip and the microstructure together, they show that the last operation was cold-work by hammering.

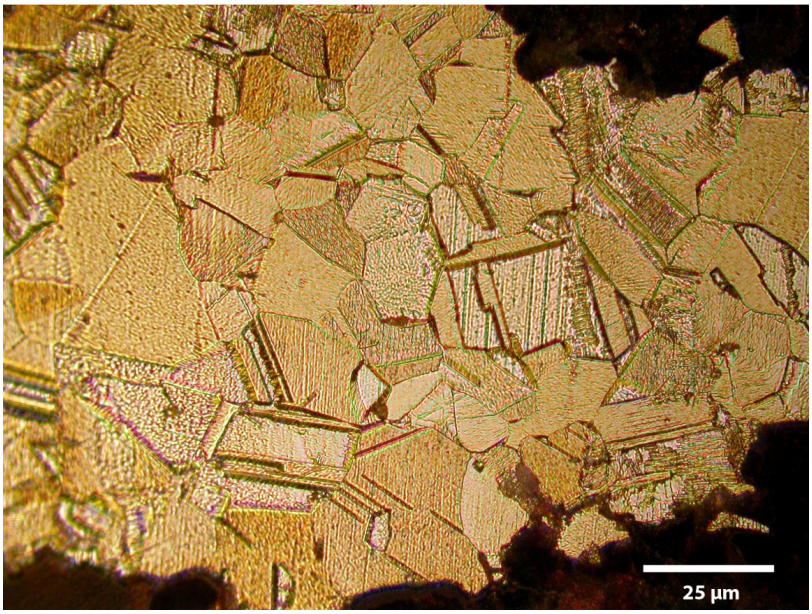

Figure 5.66 CHE349.

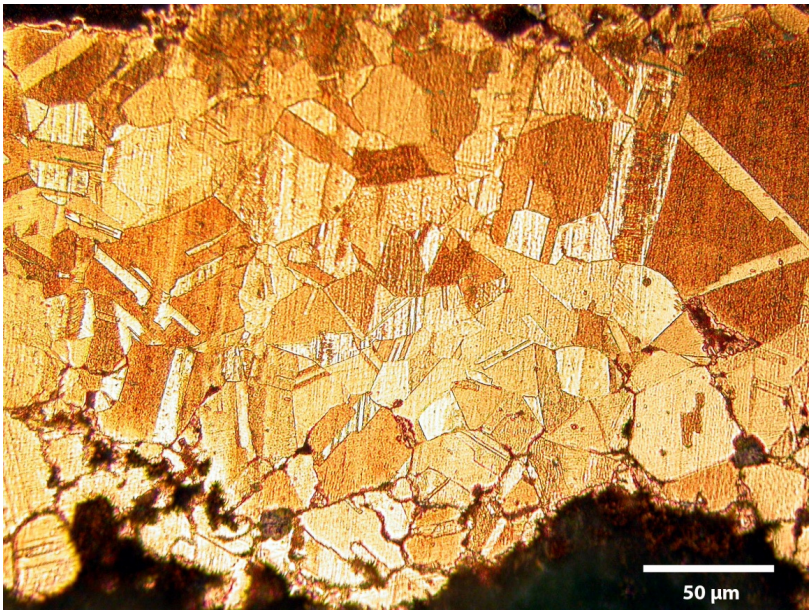

Figure 5.67 CHE701.

CHE701 is covered by a layer of copper oxides (Fig. 5.63). Since the object is made of brass, dezincification could have occurred as an initial stage of corrosion in the ground. The copper in the dezincified region then formed cuprite, sulphides and chlorides with the environment until saturation, after which metallic copper was deposited in the surface (Tylecote 1979; Wang & Merkel 2001). The copper then oxidised, leaving the outer layer than can be seen in Figure 5.68.

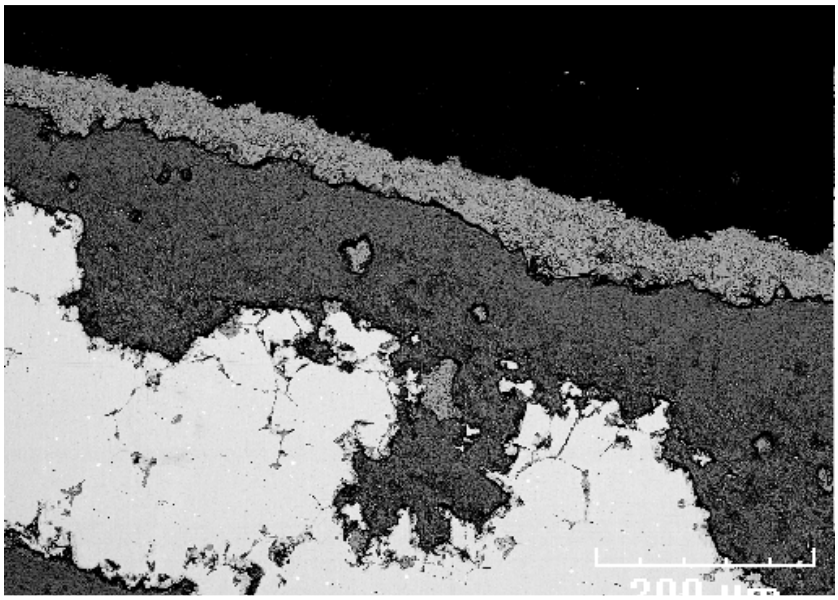

Fig 5.68 Backscattered electron image of CHE701 showing the brass in white, covered by a layer of corrosion products (copper oxides and chlorides), and an outer layer of copper oxide.

CHE848 (Fig. 5.69) is a gunmetal (14.9%Zn-2.8%Sn) *lorica segmentata* tie hook that shows a heavily deformed structure with twinning and abundant strain lines. Intergranular corrosion fractures and lead stringers can be seen running along the direction of deformation. Upon observation under the SEM, backscattered electrons show remains of plating (Fig. 5.70). A higher magnification (Fig. 5.71) shows that two layers form the remainder of the plating. EDS analysis found that the plating is a tin-lead alloy, or pewter.

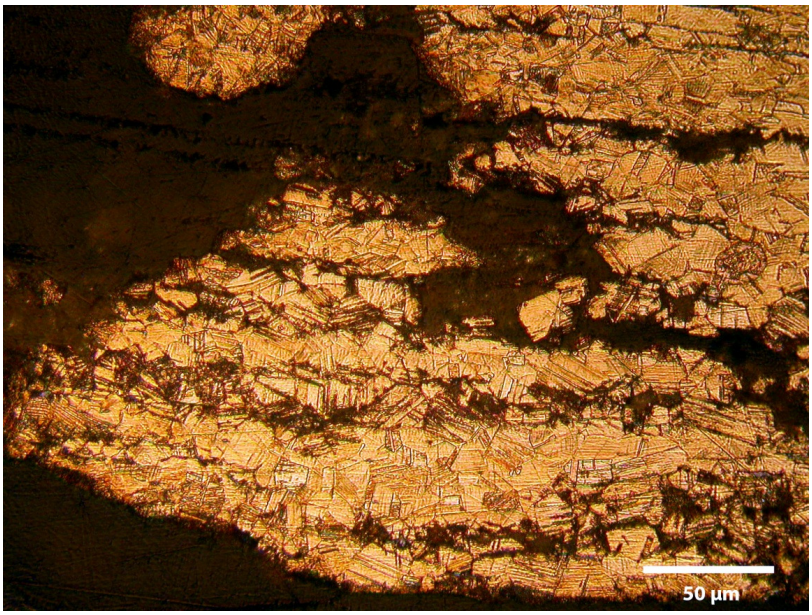

Figure 5.69 CHE848.

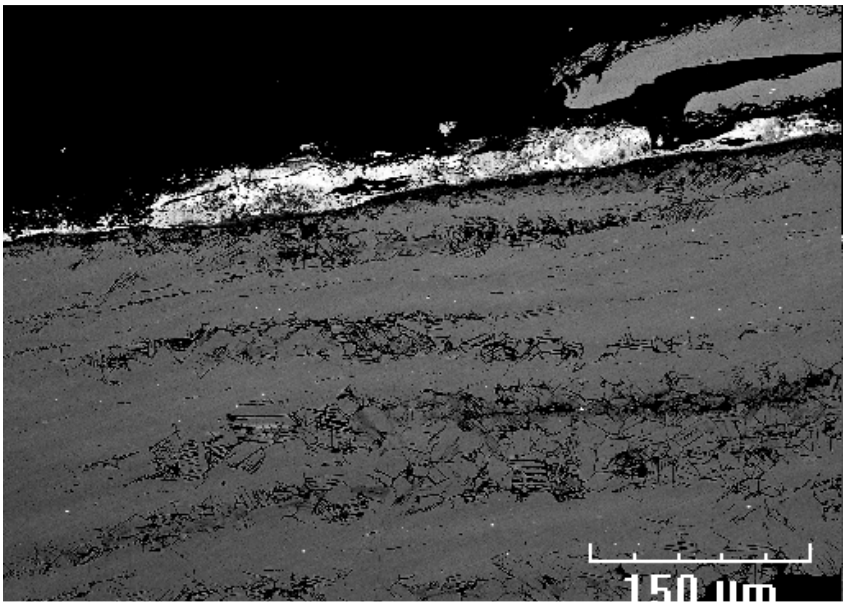

Fig 5.70 Backscattered electron image of CHE848, showing remaining tin-lead plating in white.

The thicker outer layer in Figure 5.71 has a composition of 51.5% lead, 45.5% tin and 3% copper. The thin inner layer is composed by 42.5% lead, 29% tin and 28.5% copper. Since the thin layer is in direct contact with the substrate metal of the object, it formed a Sn-Cu intermetallic compound, most likely the ε phase of the copper-tin system (Meeks 1986).

Fig 5.71 Backscattered electron image of CHE848 at high magnification, showing two distinctive layers of plating.

CHE1272 (Fig. 5.72) is a cast-bronze containing 9% tin and comprises two phases (α+δ), containing a large amount of lead (15%), which is visible as dark islands. The overall microstructure is very similar to that of CHE3, but with a higher level of lead.

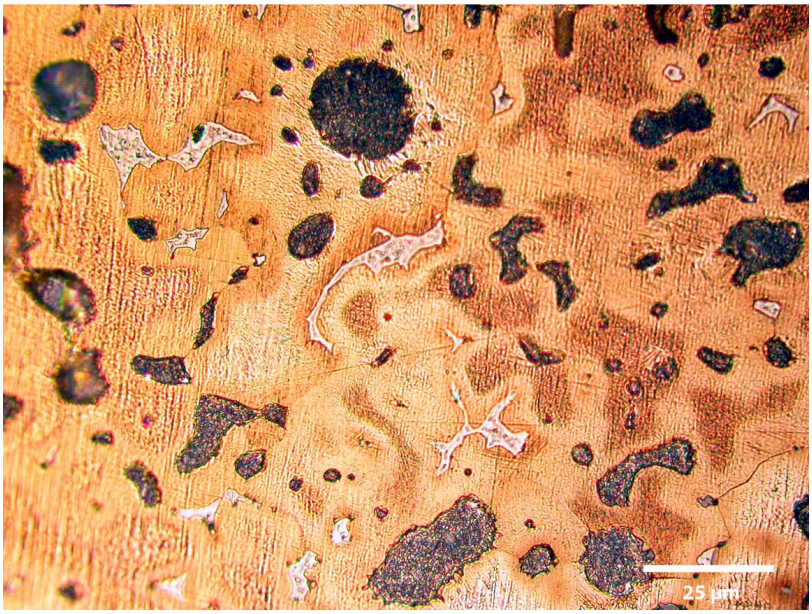

Figure 5.72 CHE1272.

CHE 1513 (Fig. 5.73) is a plated armour fitting, made of heavily deformed brass with abundant strain lines, and irregularly sized, but small grains(averaging 7µm).

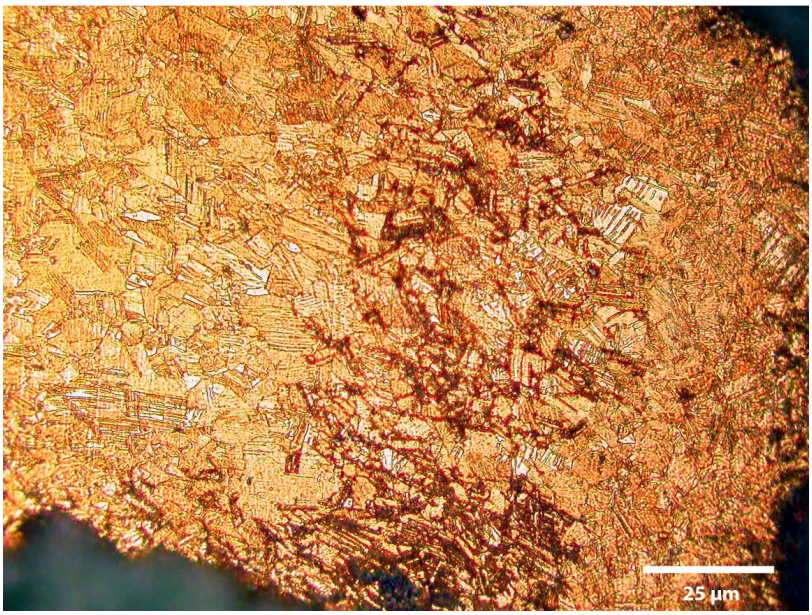

Figure 5.73 CHE1513.

The microstructure of the leaded bronze belt plate fragment CHE1516 (Fig. 5.74) is dendritic, but this is not very clear in the micrographs. The structure was heavily deformed by cold-work and strain lines completely covered the surface of the sample. The second α+δ eutectoid phase lies

between the spaces of the dendritic structure, but is not clearly visible until it is observed under the SEM (Fig. 5.75).

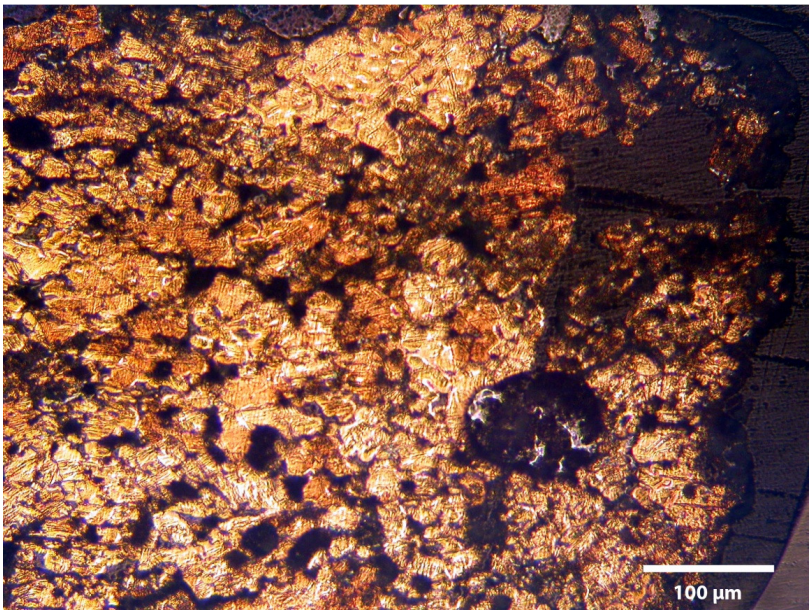

Figure 5.74 CHE1516.

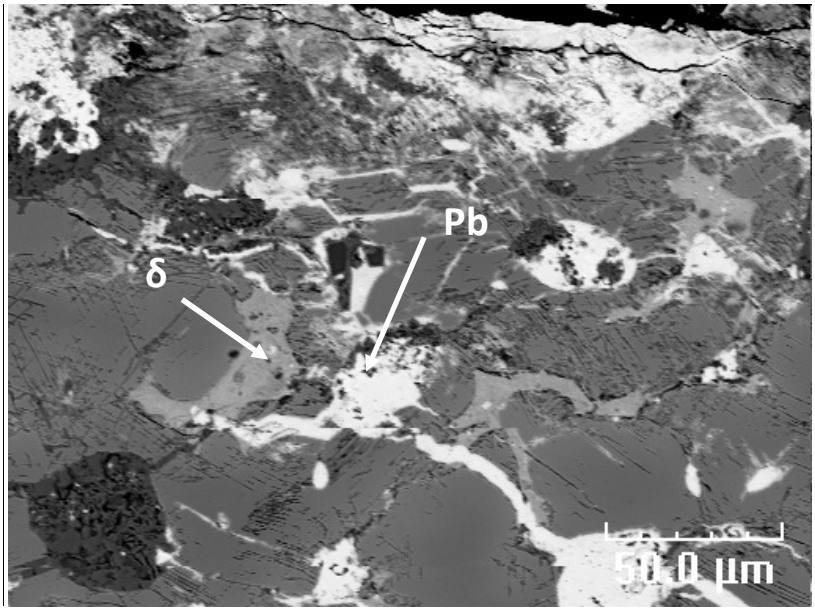

Figure 5.75 Backscattered electron image of CHE1516. White areas represent lead (insoluble in copper), while light grey shows the α+δ eutectoid phase.

A brass *lorica segmentata* hinged buckle plate, CHE1829 (Fig. 5.76) shows a twinned granular microstructure, with lead stringers showing the direction of deformation. There is intergranular corrosion in some areas of the sample, especially in the regions of higher deformation.

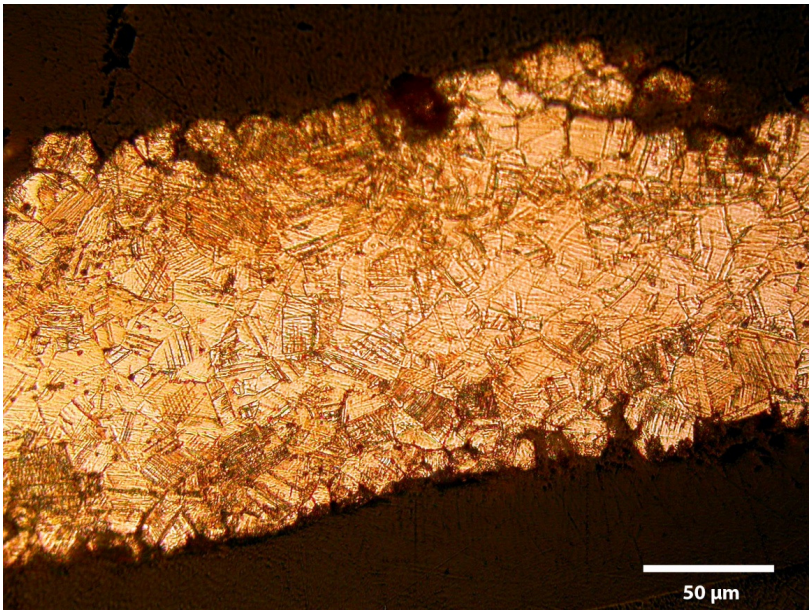

Figure 5.76 CHE1829.

CHE1833 (Fig. 5.77) is a brass belt plate with a similar grain size, but showing a higher degree of deformation. Grains are irregularly shaped and there is a greater amount of corrosion: in some areas intergranular corrosion can be seen across the middle of the sample (Fig. A3.62).

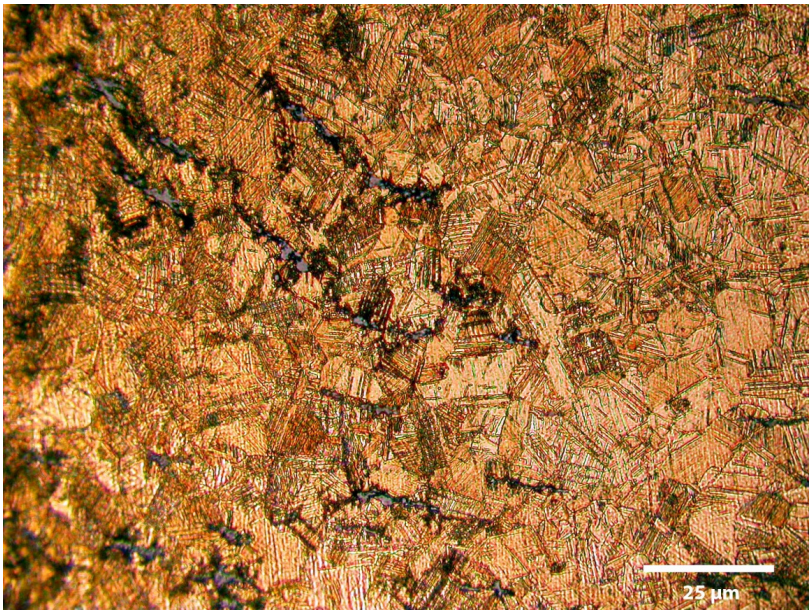

Figure 5.77 CHE1833.

CHE 1834 (Fig. 5.78) is a brass *lorica squamata* scale presenting an irregular grain size structure (from 10 to 50µm), which seems large considering the thickness of sheet metal used for scale armour. Intergranular corrosion is generalised in the sample, but the structure can still be observed. It shows only moderate deformation, even if the usual features like twinning and strain

lines are present. This brass scale is tinned, this feature being more readily visible under the electron microscope in backscattered electron mode, where it is seen in white (Figs. 5.79-80).

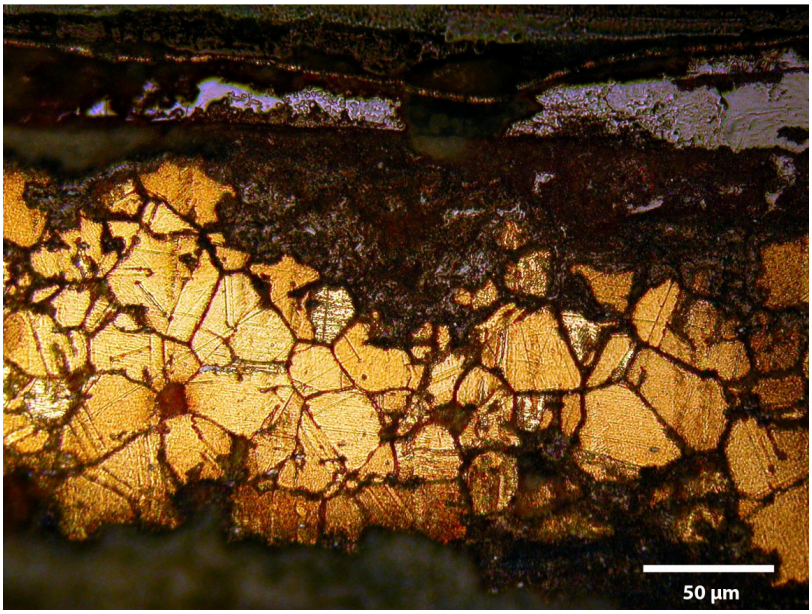

Figure 5.78 CHE1834.

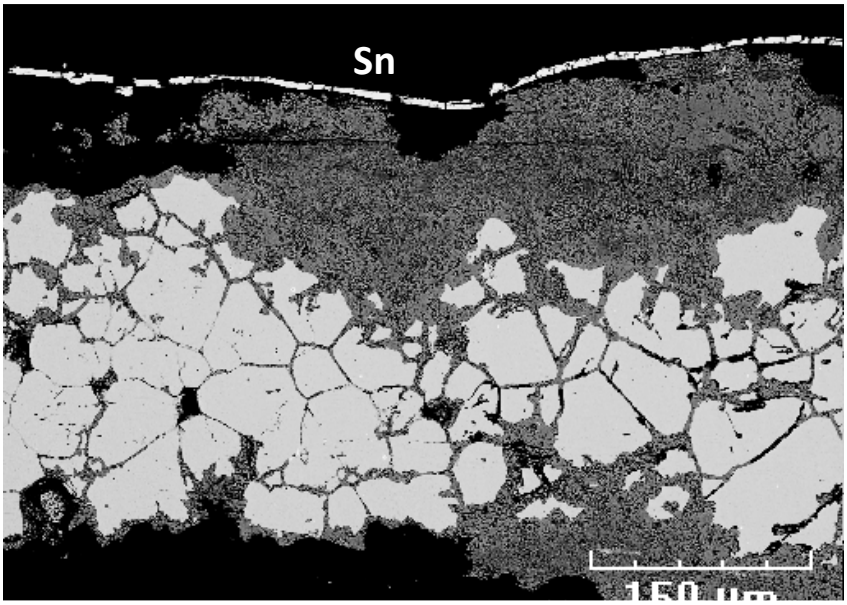

Figure 5.79 Backscattered electron image of *lorica squamata* CHE1834, showing clear tin plating over corrosion products and bulk granular structure.

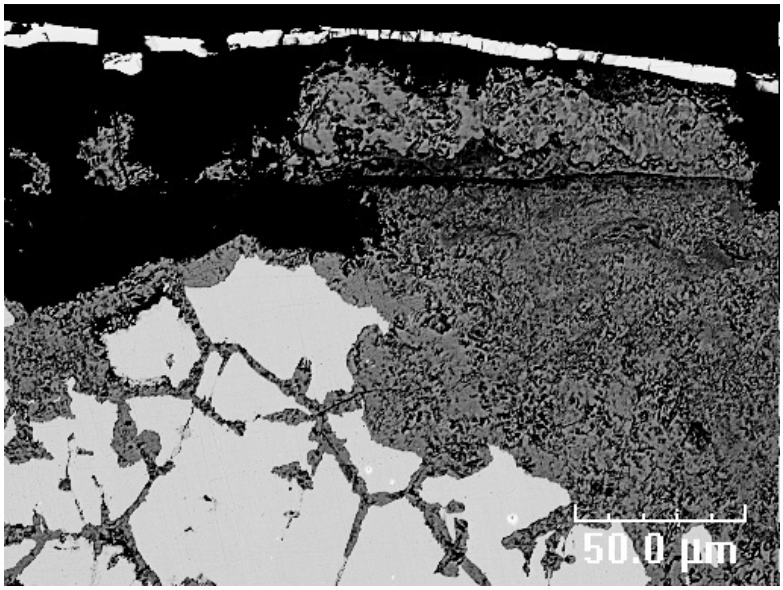

Figure 5.80 Backscattered electron images of *lorica squamata* CHE1834. High magnification. Tin plating is seen in as a white band along the upper end of the image.

The presence of tin was confirmed by semi-quantitative EDS analysis, which gives 61% copper and 39% tin. This composition, and the columnar layers of the single tinning layer, correspond to the ε-phase of the copper-tin system (62%Cu-38%tin). This suggests the tinned object was heat treated to 350°C (Meeks 1986), which contributed to relieving some of the stresses in the microstructure, but also to grain growth. The latter would have acted to the detriment of mechanical properties such as strength and hardness.

CHE1850 (Fig. 5.81) is a gunmetal pendant with a much corroded single-phase and small grained microstructure (8µm), entirely visible without the need of etchant. Intergranular corrosion is extensive, as well as intragranular corrosion along twins (Fig. 5.82).

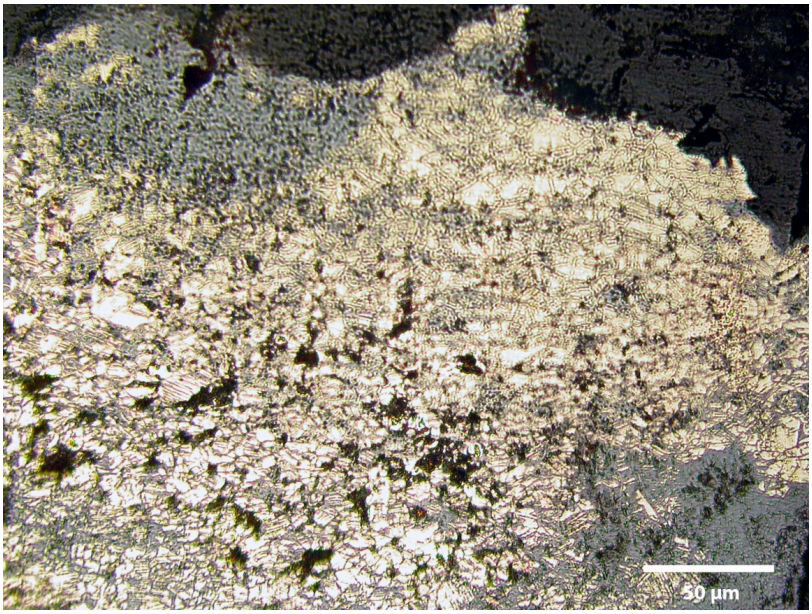

Figure 5.81 CHE1850.

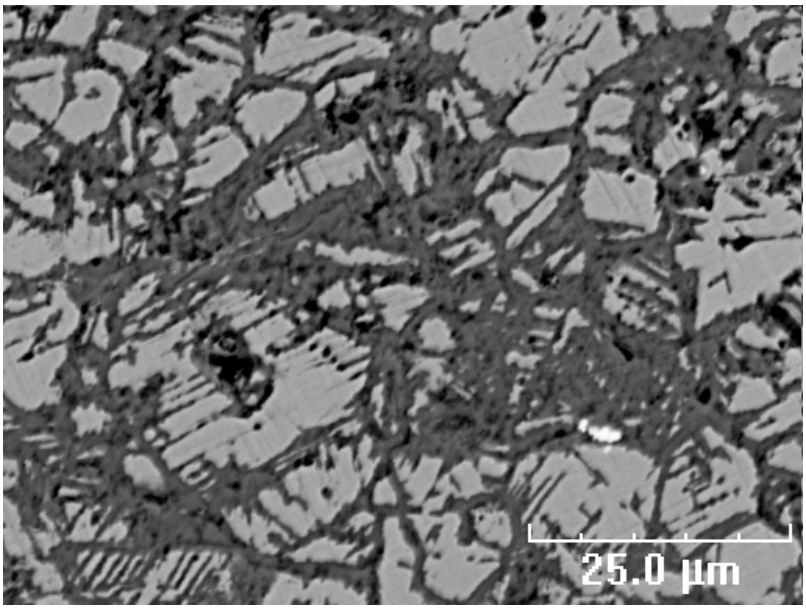

Figure 5.82 Backscattered electron image of a very corroded pendant, CHE1850 showing corrosion along twins.

CHE1855 (Fig. 5.83) and CHE2024 (Fig. 5.85) are both leaded bronze plates with similar composition and dendritic structures. The tin contents are 8% and 10% respectively, just enough for small quantities of δ-phase to appear (Figs. 5.84 & 5.85). The main metallographic difference however, is the degree of deformation and size of the dendritic crystals. In the case of CHE1855, dendrites are oriented transversally to the sample, and are large (between 50 and 100µm wide) and only slightly deformed. In contrast, CHE2024 shows distorted 30µm wide dendrites oriented longitudinally to the sample by cold working.

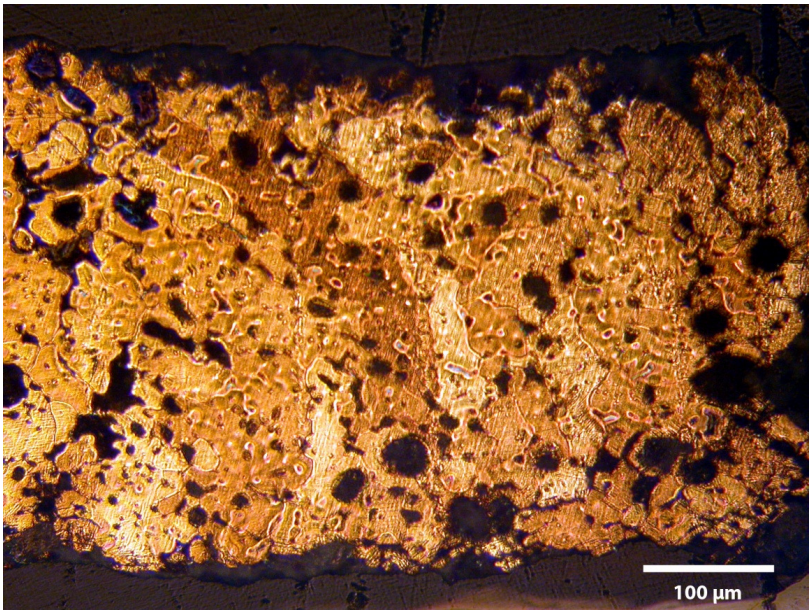

Figure 5.83 CHE1855.

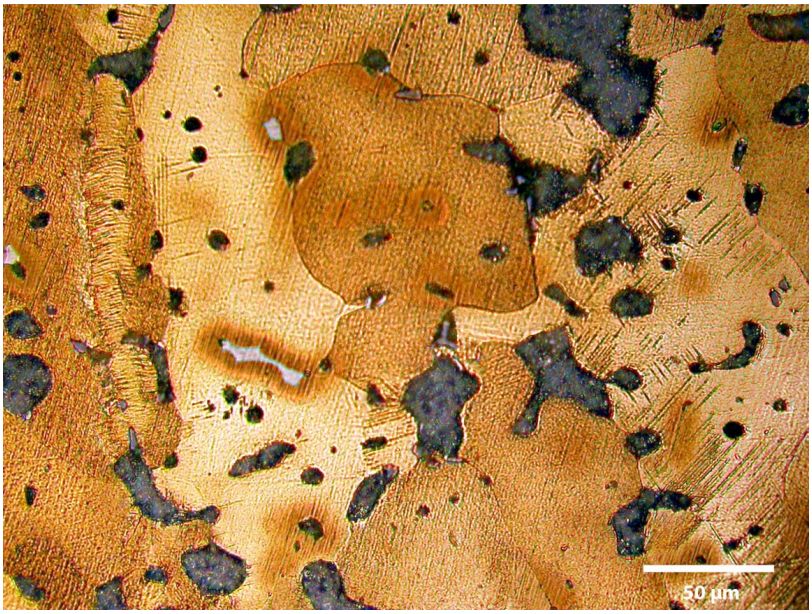

Figure 5.84 CHE1855.

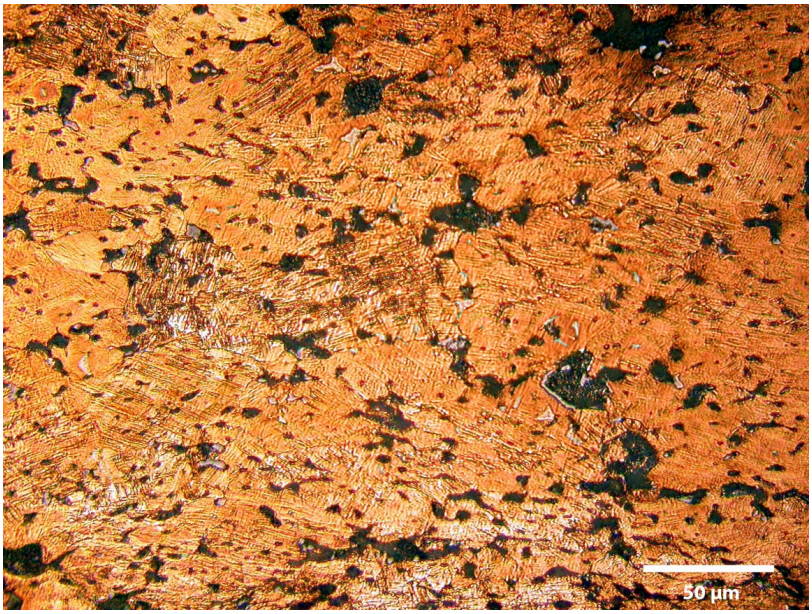

Figure 5.85 CHE2024.

CHE2171 (Fig. 5.86) and CHE2711 (Fig. 5.87) are two pendants, the first made of brass, and the second a low-tin gunmetal. They both show a granular structure and moderate amount of strain lines. However, they differ substantially in grain size. Whilst grains are 28µm in average diameter for CHE2171, grains are extremely small in the case of CHE2711, suggesting that the structure recrystallized prior to the last cold-working operation.

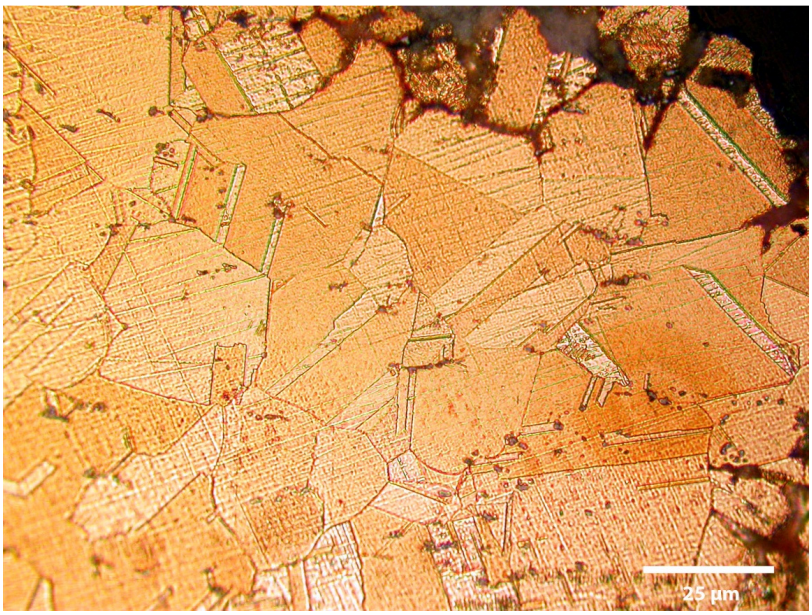

Figure 5.86 CHE2171.

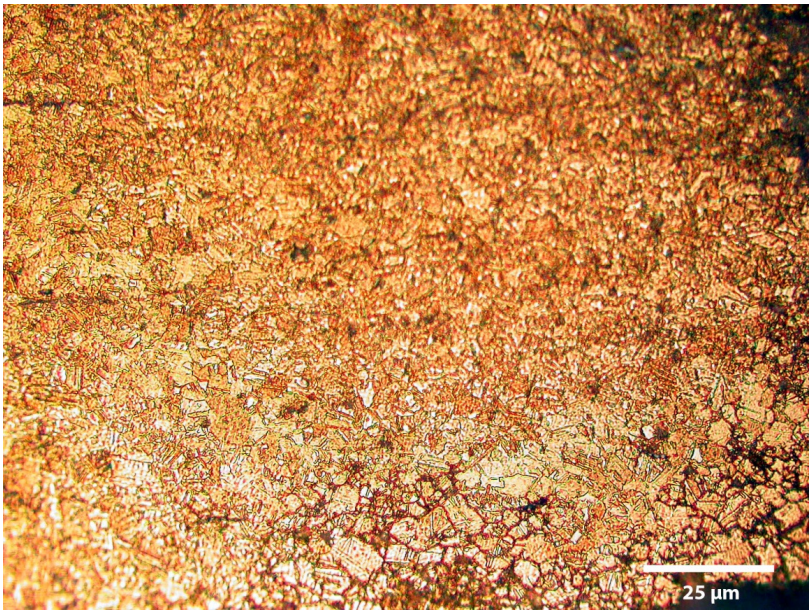

Figure 5.87 CHE2711.

CHE8869 (Fig. 5.88) is a very corroded gunmetal harness strap distributor, showing a coarse dendritic structure with large lead globules a very small presence of δ-phase due to its 7.5% tin, as seen in Figure 5.89. Lead is seen as white globules and the tin-rich phase is shown in light grey.

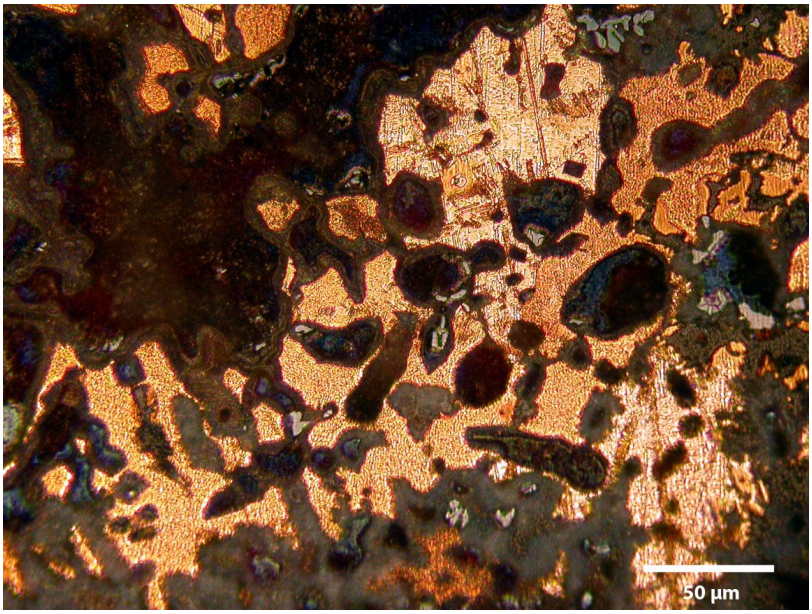

Figure 5.88 CHE8969.

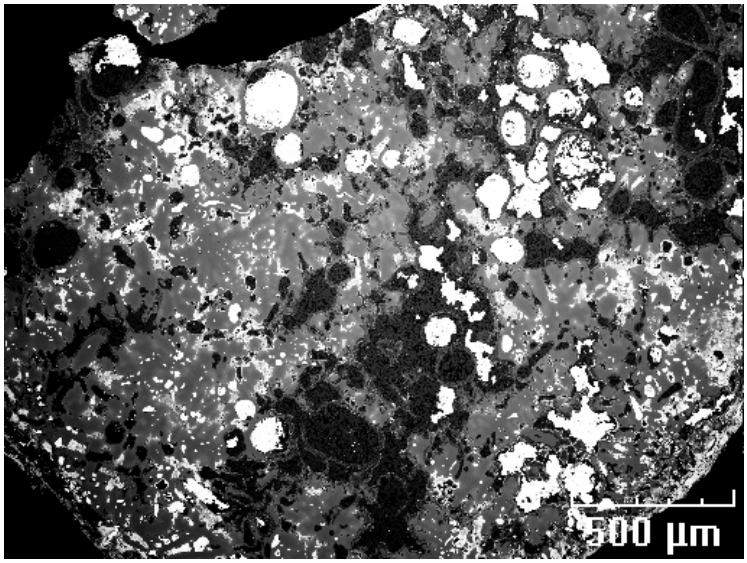

Figure 5.89 Backscattered electron image of horse harness fitting CHE8969, showing a very corroded structure dominated by coarse dendrites and large lead globules.

Grain Size

The spread of grain sizes found in all Chester objects that have a granular structure can be seen in Figure 5.90. Belt fittings show the largest grain size, *lorica segmentata* fittings show a large spread in their grain sizes, which are roughly similar to those from *lorica squamata* samples. Surprisingly, horse harness pendants with granular structure have the smallest grains, but these seem to be a product of recrystallization after cold work. Both the *lorica squamata* scales and the *lorica segmentata* fittings have small and distorted grains due to cold work, which improves mechanical properties such as strength and hardness.

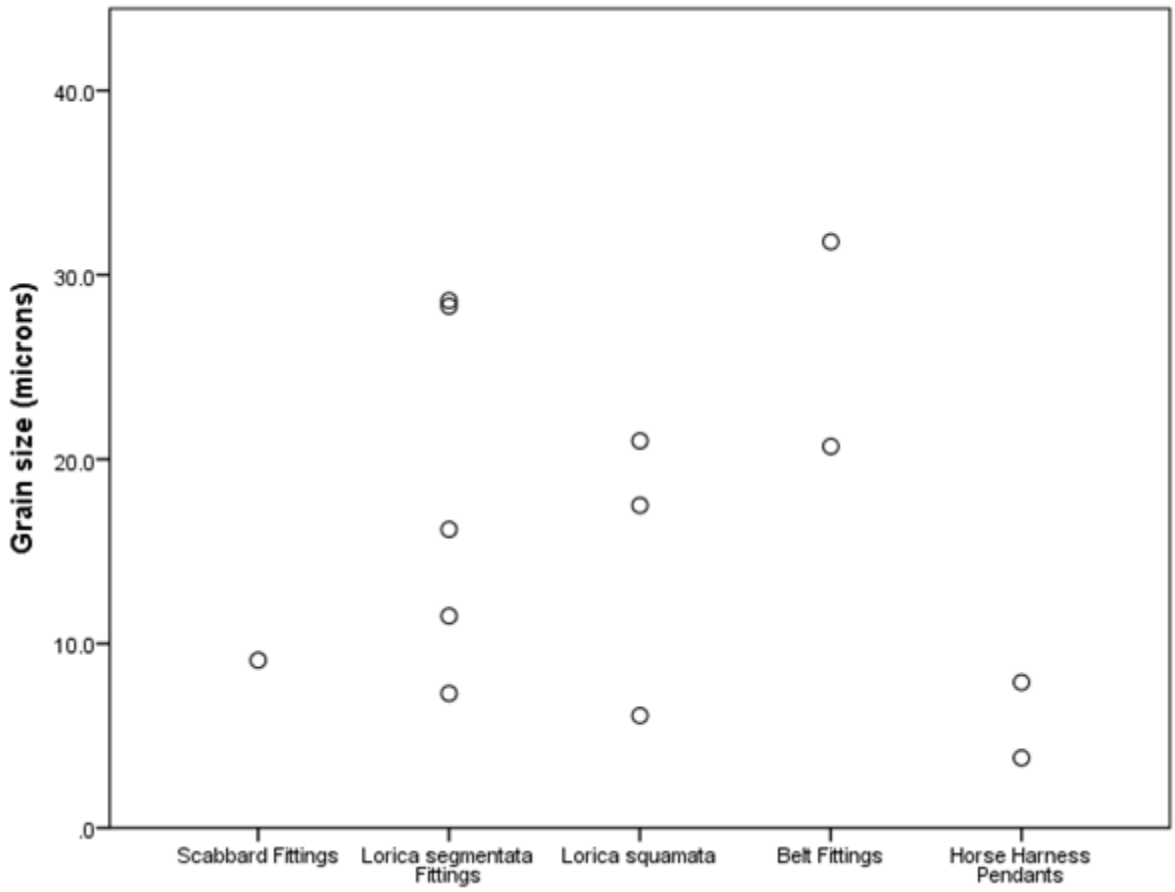

Figure 5.90 Distribution of grain size by object type, for granular structure samples for Chester.

5.8 Kingsholm

5.8.1 AAS Results (Table A2.6)

5.8.1.1 Alloy type

More than half of the analysed objects from Kingsholm are brasses (57%), followed by gunmetals, which represent a quarter of the total objects (Fig. 5.91). The rest is evenly divided between un-alloyed copper (10%) and bronzes (9%). 16% of the samples are leaded, which are mostly gunmetals, followed by leaded bronzes and leaded gunmetals.

Lorica segmentata fittings constitute 40% of the brasses analysed. The rest are shared by horse harness fittings, belt and apron fittings, and metal sheet. Gunmetals are dominated by horse harness equipment (mostly leaded), but also three *lorica segmentata* fittings were found made of this alloy. The distribution of the zinc content in the brasses from Kingsholm presents a bi-modal distribution (Fig. 5.92), with peaks at 21% and 17.5% and zinc. These are likely to represent fresh and secondary brass, respectively.

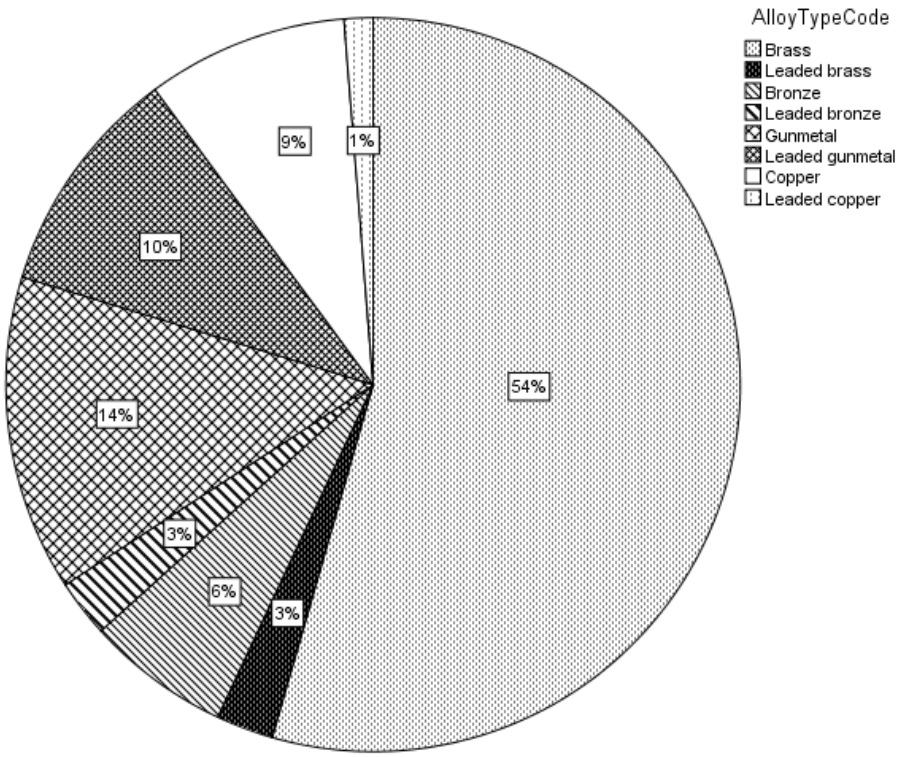

Figure 5.91 Distribution of objects from Kingsholm (analysed by AAS) by alloy type.

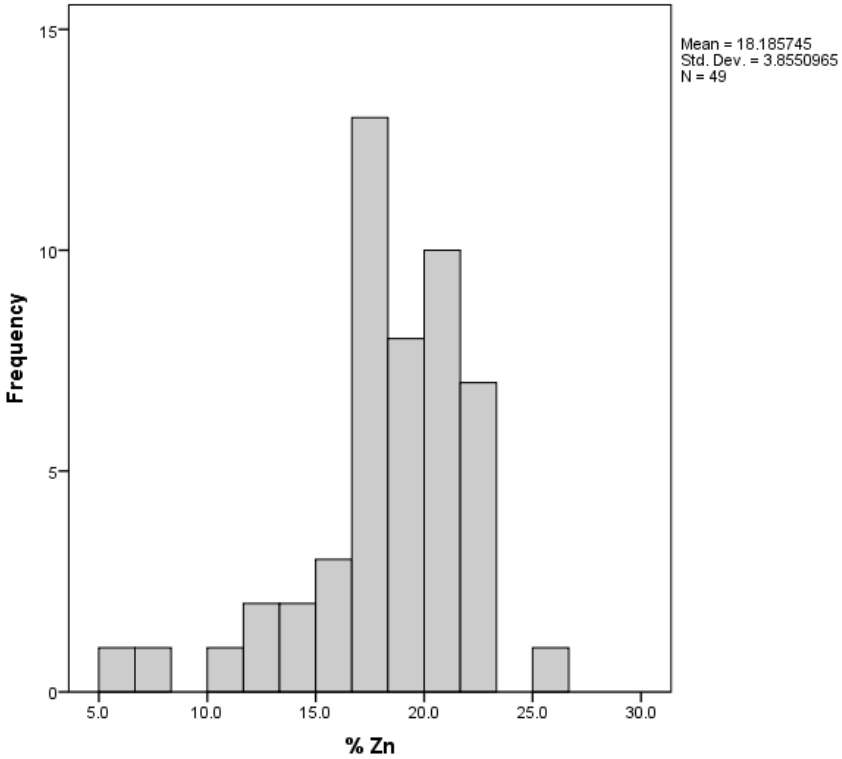

Figure 5.92 Distribution of zinc in brass objects from Kingsholm.

The eight un-alloyed copper objects include horse harness equipment, a *lorica segmentata* fitting, binding and plate fragments. In the case of the bronze objects, the best represented are horse harness fittings, but also a buckle, a *lorica segmentata* hinge and a folded strip.

A typical inverse correlation can be seen between tin and zinc, accounting for 76% of the objects (Fig. 5.93) and the leaded objects are included in this behaviour (Fig. 5.94). Of the four brasses with less than 15% of zinc that do not fit into the correlation, two belong to scabbard fittings, whilst the remaining two are an apron fitting and crescent shaped horse-harness mount.

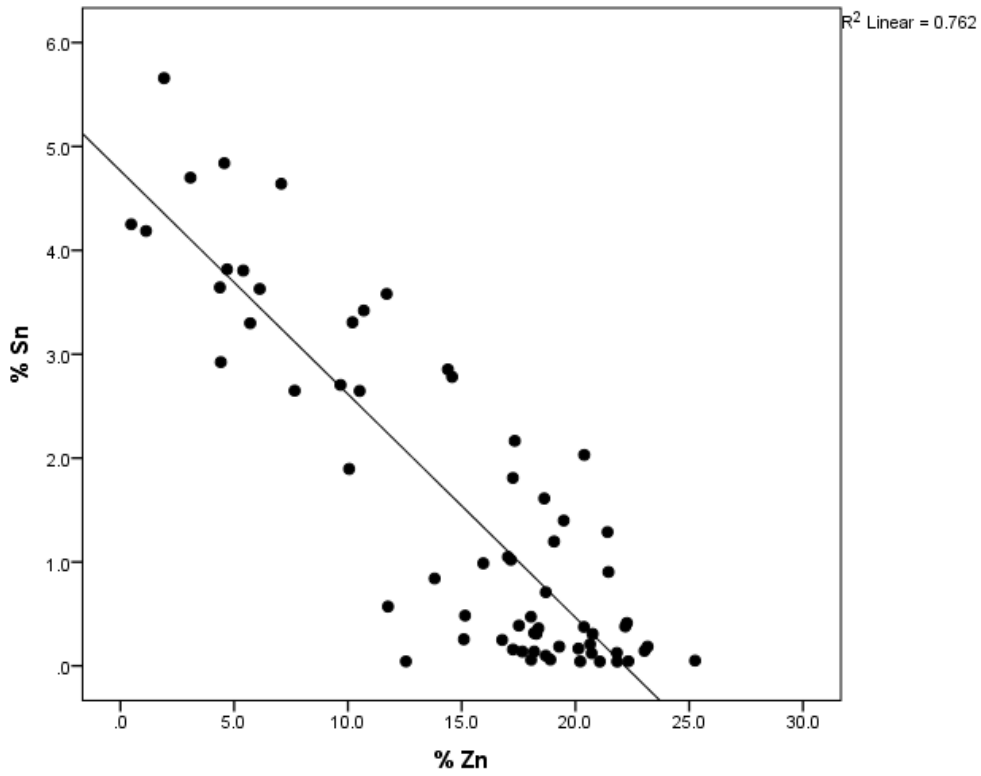

Figure 5.93 Zinc v. tin for objects from Kingsholm, showing an inverse correlation with linear regression curve and coefficient.

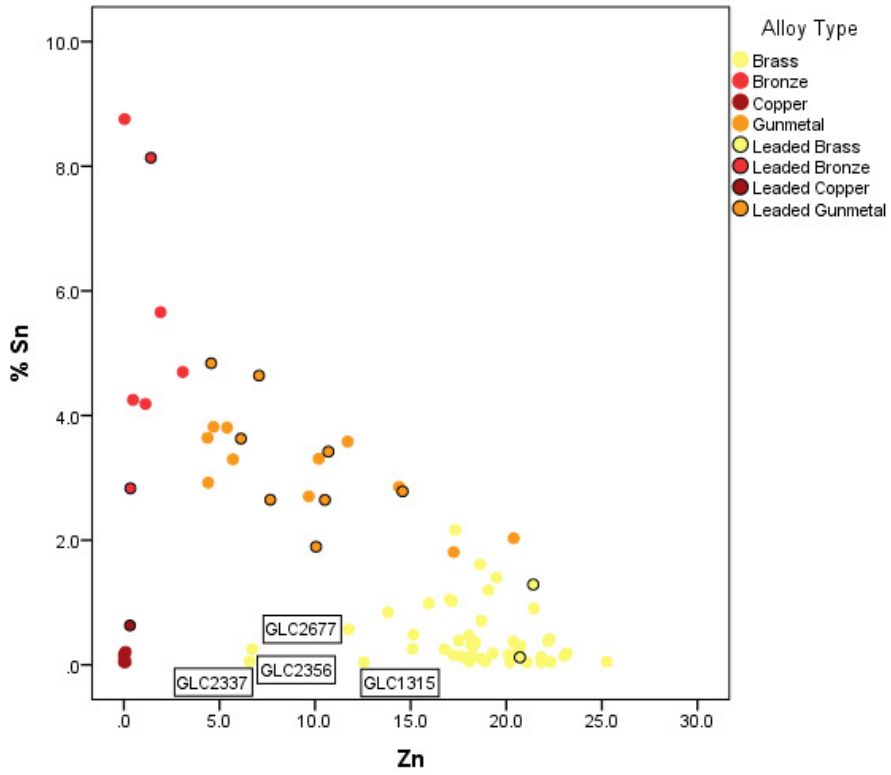

Figure 5.94 Zinc v. tin for objects from Kingsholm, showing an inverse correlation for bronzes, brasses and gunmetals.

5.8.1.2 Traces

Since antimony and lead do not show any correlation (Fig. 5.95), the antimony in the alloys can be assumed to originate from the copper in the alloy, and therefore it can be re-scaled to the copper for bivariate analysis.

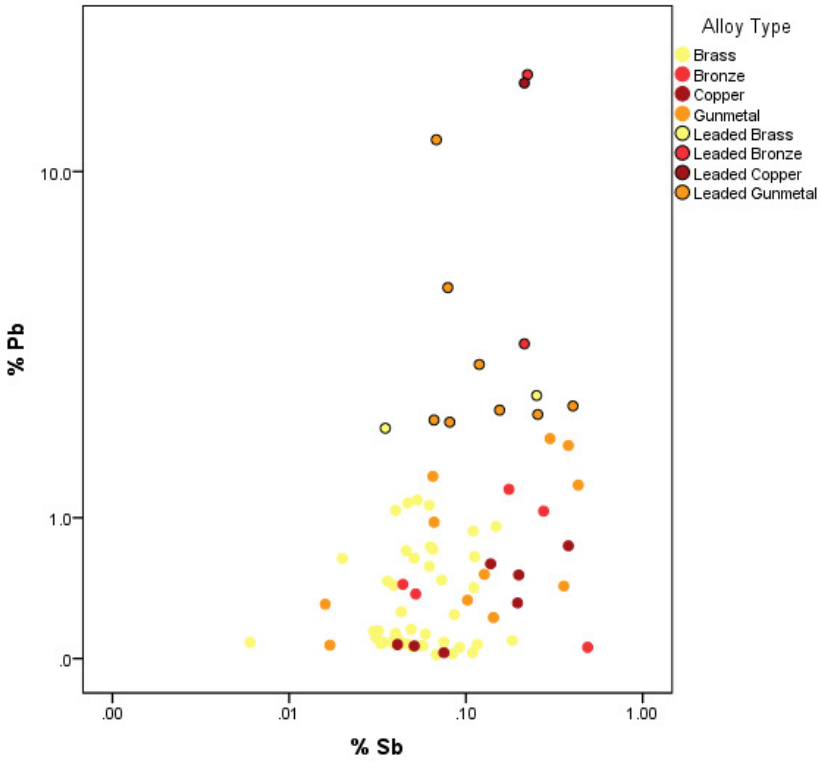

Figure 5.95 Antimony v. lead percentage for objects from Kingsholm.

Figure 5.96 shows that there is a group of gunmetals and brasses that is separate from the rest by having higher nickel content. The objects forming this group are a *lorica segmentata* fitting, a binding fragment and miscellaneous plate fragments.

When two pairs of elements are plotted against each other, nickel v. antimony (Fig. 5.97), and nickel v. arsenic (Fig. 5.98), positive correlations can be seen between the elements in both cases. In the case of nickel v. arsenic, the correlation is apparent once arsenic is above the limit of detection.

In both the nickel v. antimony plot (Fig. 5.97) and when plotting arsenic v. antimony (Fig. 5.99) it can be seen that there is group separation by alloy type defined by the antimony content. This is formed mainly by gunmetals and bronzes, which are not the dominant alloy in the assemblage. This disproportion makes the supposition of group separation stronger. These objects are *lorica segmentata* and strap fittings, and a buckle.

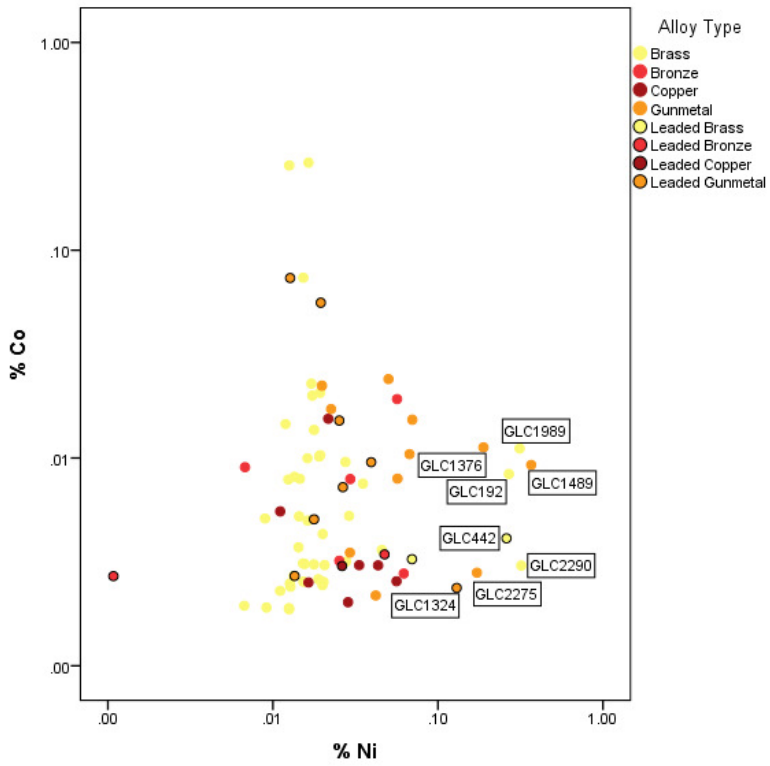

Figure 5.96 Kingsholm. Nickel v. cobalt bivariate plot, with both elements re-scaled to the copper.

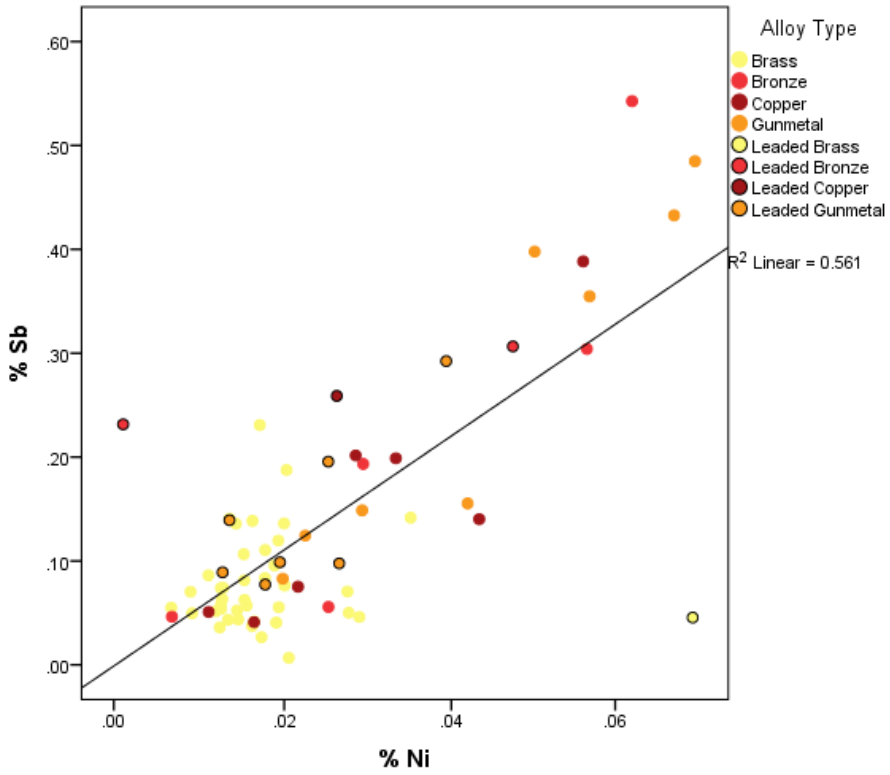

Figure 5.97 Kingsholm. Nickel v. antimony bivariate plot by alloy type, with both elements re-scaled to the copper.

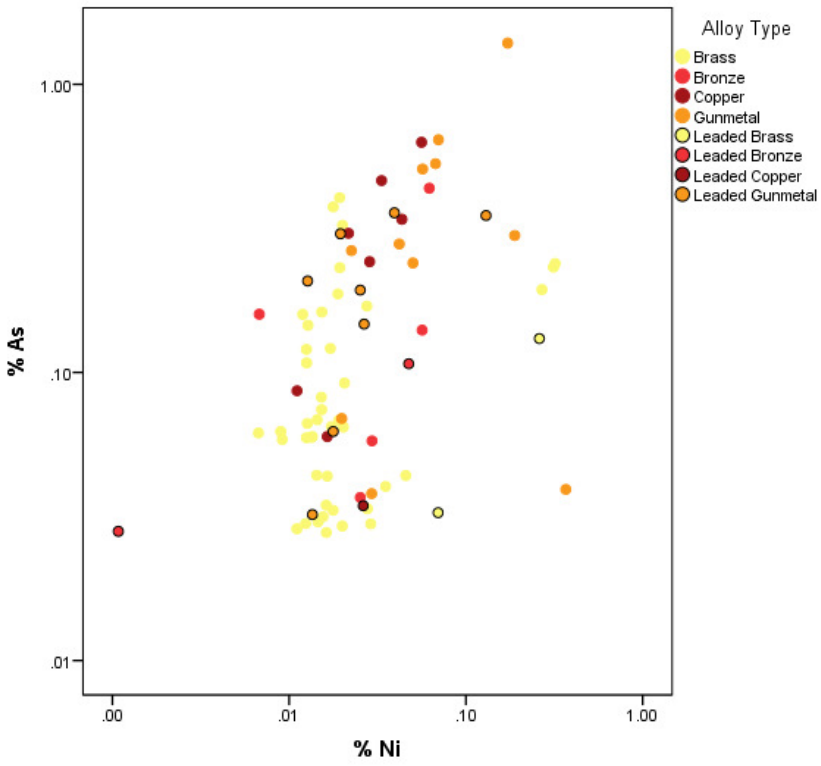

Figure 5.98 Kingsholm. Nickel v. arsenic bivariate plot by alloy type, with both elements re-scaled to the copper.

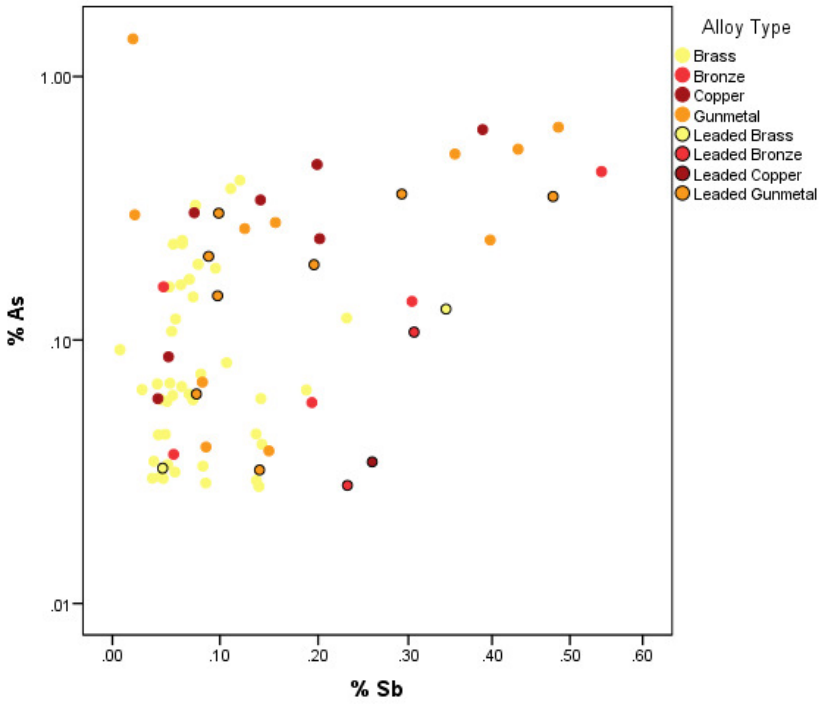

Figure 5.99 Kingsholm. Antimony v. arsenic bivariate plot by alloy type, with both elements re-scaled to the copper.

Group separation by alloy type seems to also exist for another trace element, silver (Fig. 5.100), where most brasses seem to have lower nickel and silver content than most gunmetals and bronzes.

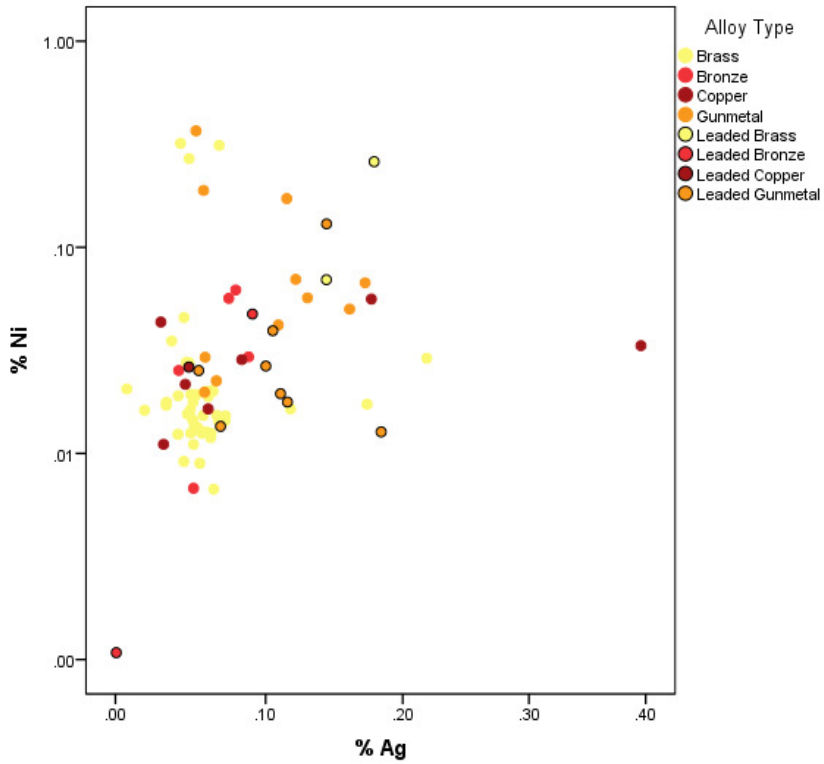

Figure 5.100 Kingsholm. Silver v. nickel bivariate plot, with both elements re-scaled to the copper.

5.8.2 Metallography

GLC48 (Fig. 5.101) is a brass decorated rosette with 2% lead. The structure is granular and shows strain lines and moderate deformation. The grains are very irregular and show twinning, revealing cycles of cold-working and annealing. Lead is visible as elongated features in the direction of deformation and is best seen in backscattered electron mode (Fig. 5.102).

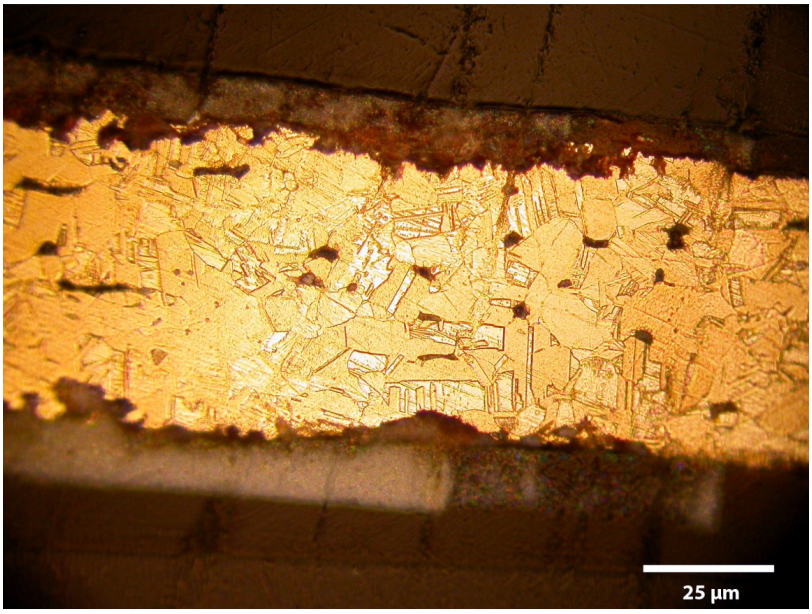

Figure 5.101 GLC48.

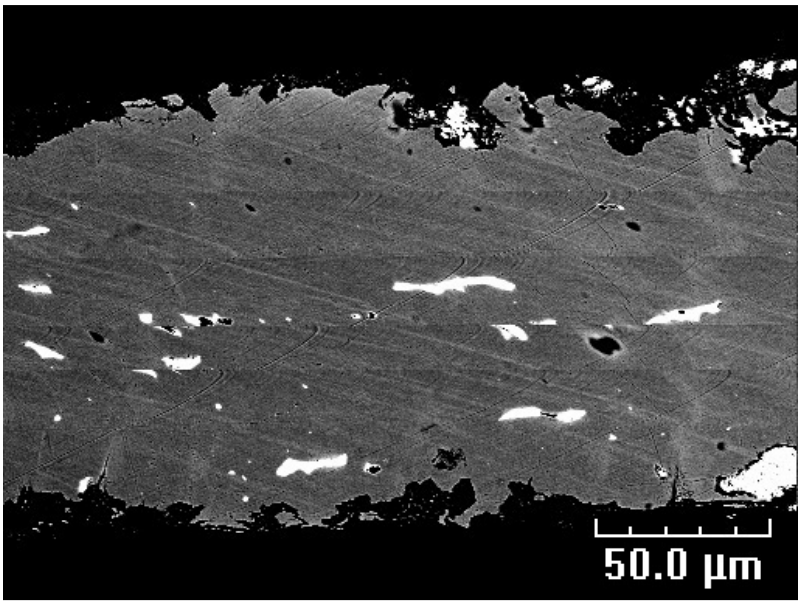

Figure 5.102 Backscattered electron image for GLC48, showing lead (in white) along oriented along the direction of deformation.

GLC161 (Fig. 5.103) is a brass *lorica segmentata* plate that has a granular structure twice as large as rosette GLC48. The structure shows more strain lines, but the grains are less deformed. The last cold-working operation was probably more substantial than those from the previous cycles.

Figure 5.103 GLC161.

GLC442 (Fig. 5.104) is a fragment from a pendant catch plate. An as-cast structure with fine dendrites that grew towards the middle of the sample can be seen. Corrosion in the sample is generalised, but it is severe near the surface, where interdendritic spaces are completely mineralised, as they are preferentially corroded over the dendrites (Fig. 5.105).

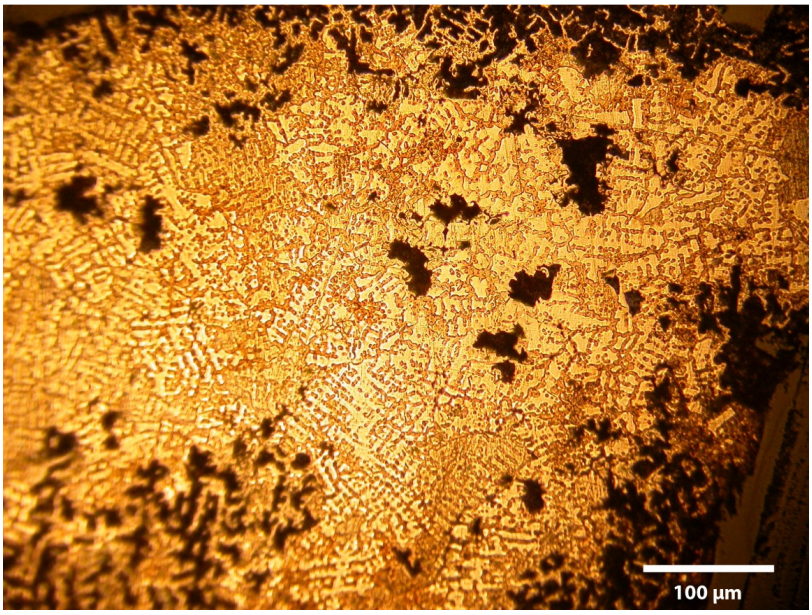

Figure 5.104 GLC442.

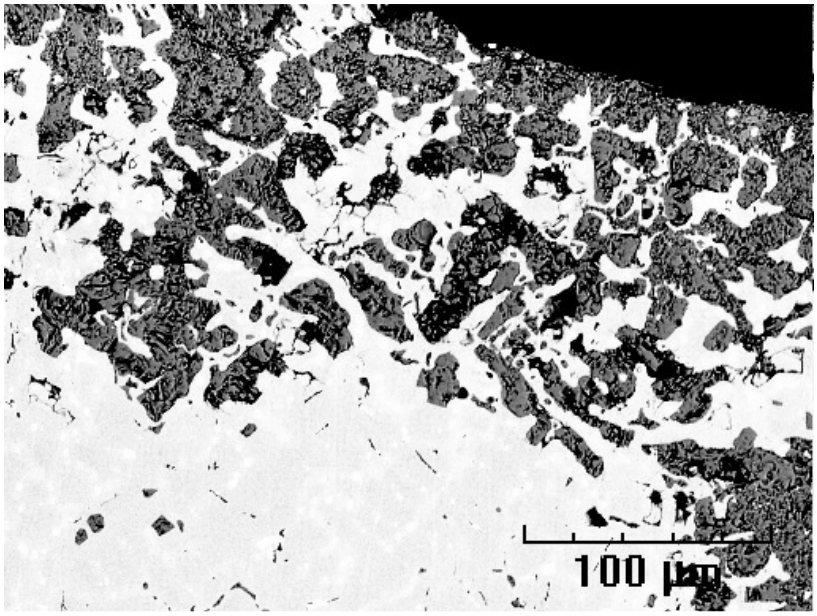

Figure 5.105 Backscattered electron image of GLC442, showing a dendritic structure with corroded interdendritic space.

GLC813 (Fig. 5.106) is a low tin bronze horse harness strap fastener showing a partially re-crystallised structure. The new extremely small grains are situated towards the middle of the sample (Fig. 5.107). As the outer regions of the sample are approached, dendritic structures (very deformed and showing abundant strain lines) can be seen. After casting, the object was probably cold-worked and then reheated again, causing partial recrystallisation. The dendritic structure can be clearly seen using backscattered electrons (Fig. 5.108).

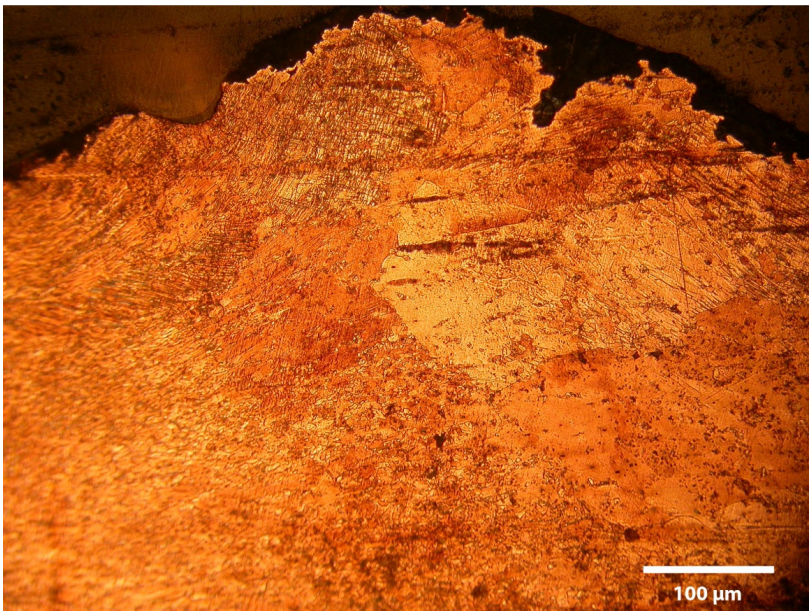

Figure 5.106 GLC813.

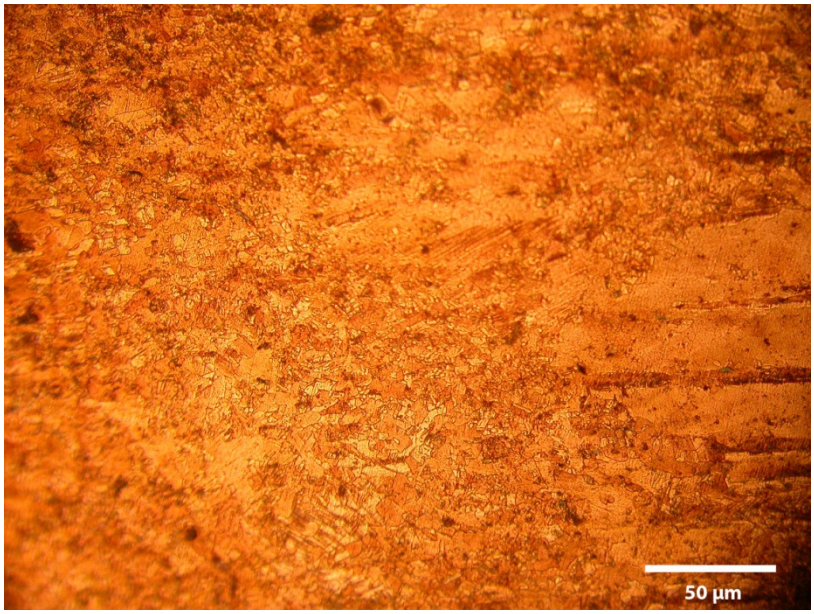

Figure 5.107 GLC813.

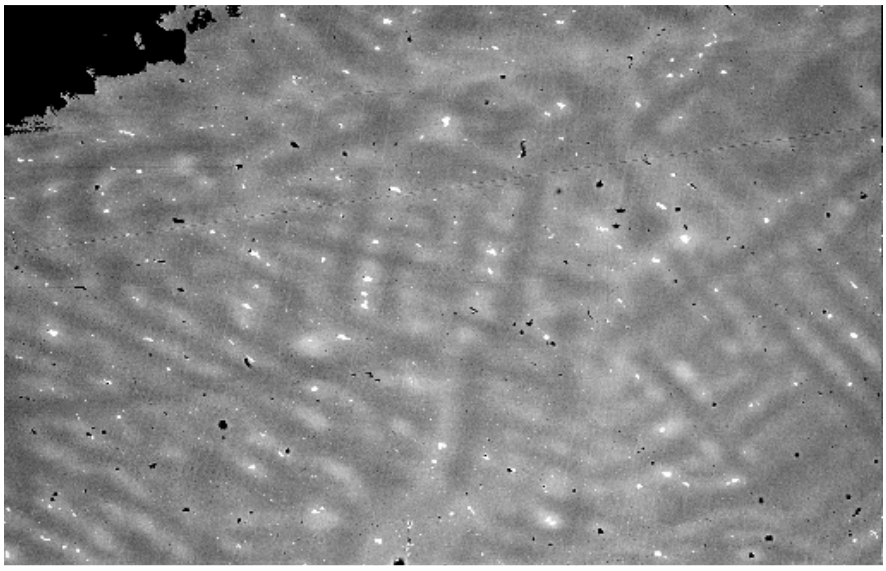

Figure 5.108 GLC813. Dendritic structure from a partially recrystallised bronze horse harness fitting.

GLC846 (Fig. 5.109) is a brass shield binding showing a granular structure with extensive intergranular corrosion. Grains are distorted and their size is small (9µm).

Figure 5.109 GLC846.

GLC1099 (Fig. 5.110) is a bronze *lorica segmentata* hinged fitting that shows larger grains (but more irregular) than the shield binding mentioned above and a less corroded microstructure. Lead stringers can be seen, revealing the overall direction of deformation through the different cycles of cold-work and reheating.

Figure 5.110 GLC109.

GLC1176 (Fig. 5.111) is a gunmetal horse-harness double-spectacle strap fastener that shows a dendritic structure. The dendrites are coarse, and were cold-worked, as shown by strain lines present on some of them.

Figure 5.111 GLC1176.

GLC1234 (Fig. 5.112) is a brass buckle plate with a distorted structure. It shows mid-sized (25µm) irregular grains that are moderately distorted in shape. The strain lines are generalised, but not very abundant.

Figure 5.112 GLC1234.

GLC1376 (Fig. 5.113-4) is a brass *lorica segmentata* hinged plate showing a medium-sized granular structure (25µm) with heavy deformation and a high presence of strain lines. At an edge flattened by cold work, deformation is extremely heavy, as can be seen by the banded structure that the area shows (Fig. 5.114).

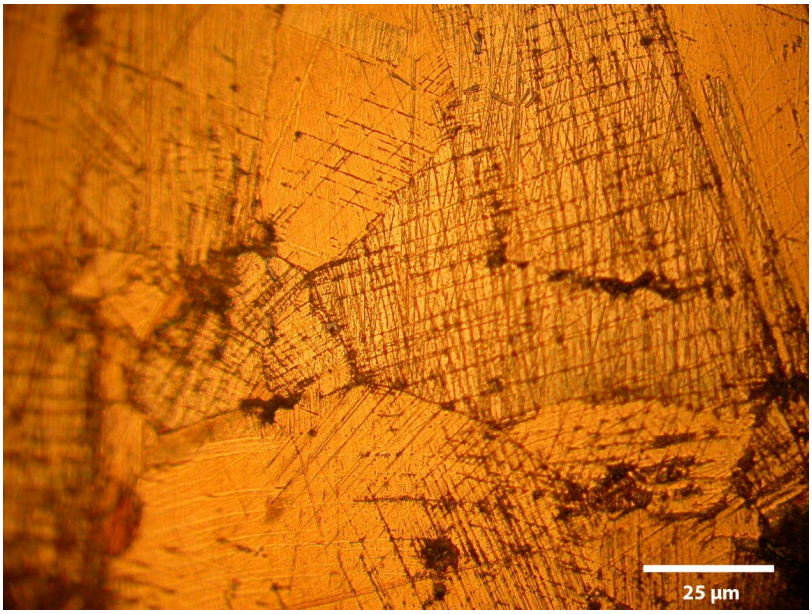

Figure 5.113 GLC1376.

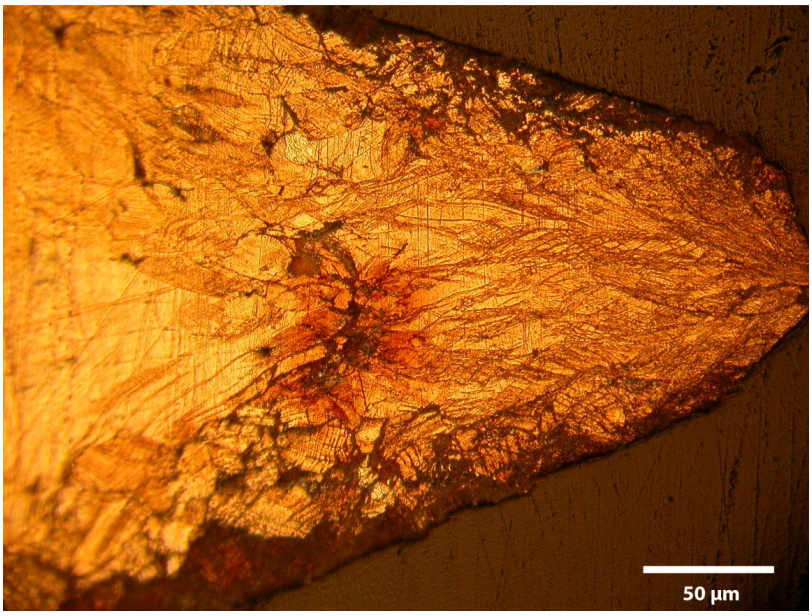

Figure 5.114 GLC1376.

A rectangular plate, GLC1489 (Fig. 5.115), a *lorica segmentata* hinged plate GLC1533 (Fig. 5.116), and a belt plate GLC1579 (Fig. 5.117), are all made of brass and show the expected features for sheet-metal brass objects; deformed twinned grains with slip lines, and insoluble lead globules. The difference are a double grain size for the rectangular plate (22µm) when compared to the other two, and a higher degree of deformation in the case of the *lorica* plate.

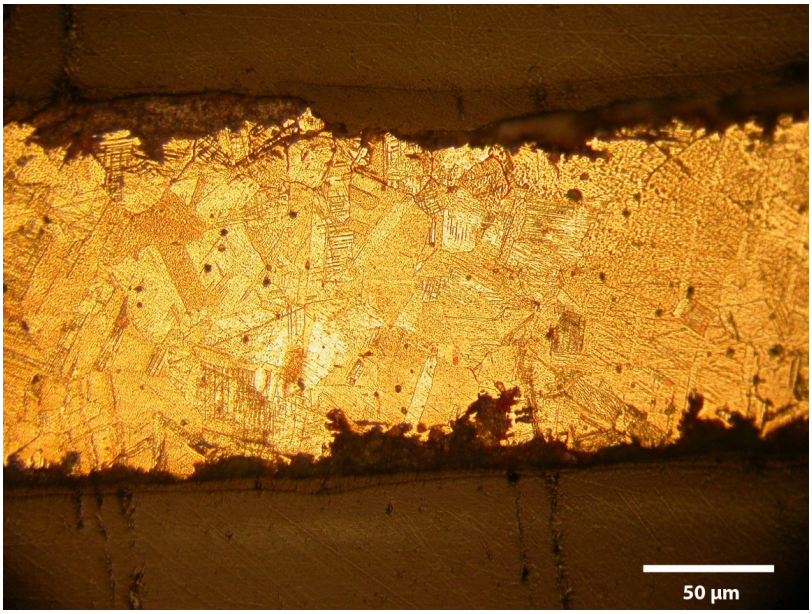

Figure 5.115 GLC1489.

Figure 5.116 GLC1533.

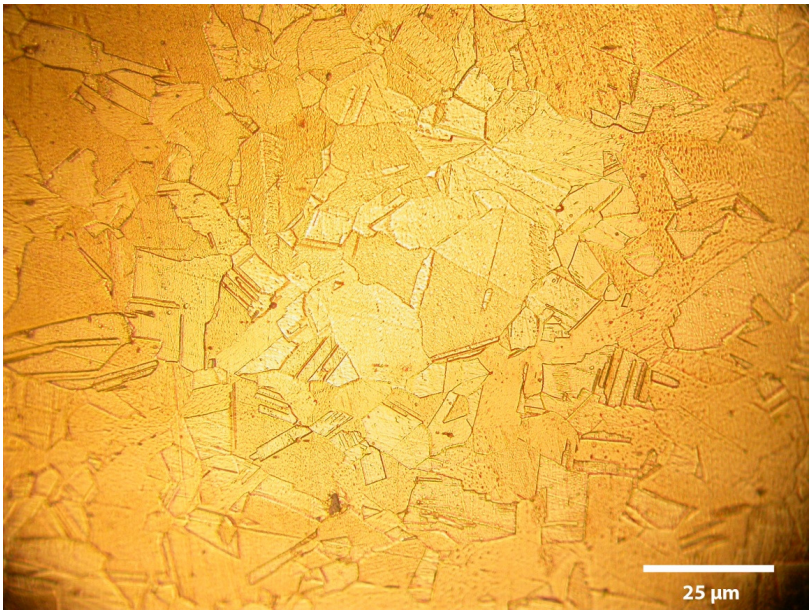

Figure 5.117 GLC1573.

GLC1683 (Fig. 5.118) is a bronze scabbard chape. The object was cast, as its dendritic structure indicates, and was cold-worked to its final shape. Deformed dendrites and strain lines attest to this process.

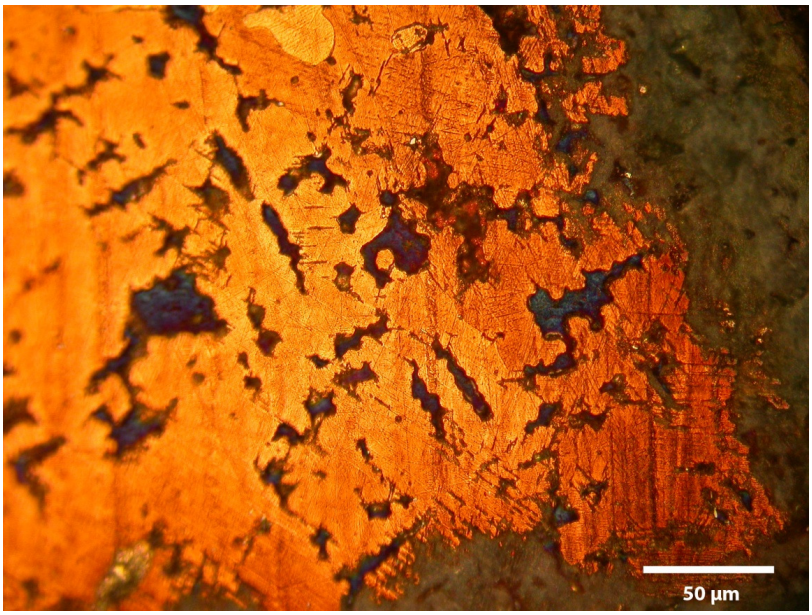

Figure 5.118 GLC1683.

GLC1685 (Fig. 5.119) is a thin brass metal strip from a scabbard. Its microstructure is granular with very small grains (7µm), but few strain lines are visible. It seems that the strip was heated as one of the last steps in its manufacturing history.

Figure 5.119 GLC1685.

GLC2136 (Fig. 5.120) is a fragment of copper binding. The etched surface reveals a microstructure with very small grains (7µm). The sample also shows the cross section where the metal sheet bends (Fig. 5.121). Here distorted and elongated grains can be seen, indicating that the binding was cold-worked to shape. It seems that this binding was silvered, as suggested by EDS analysis on a particle found at a surface (Fig. 5.122-3).

Figure 5.120 GLC2136.

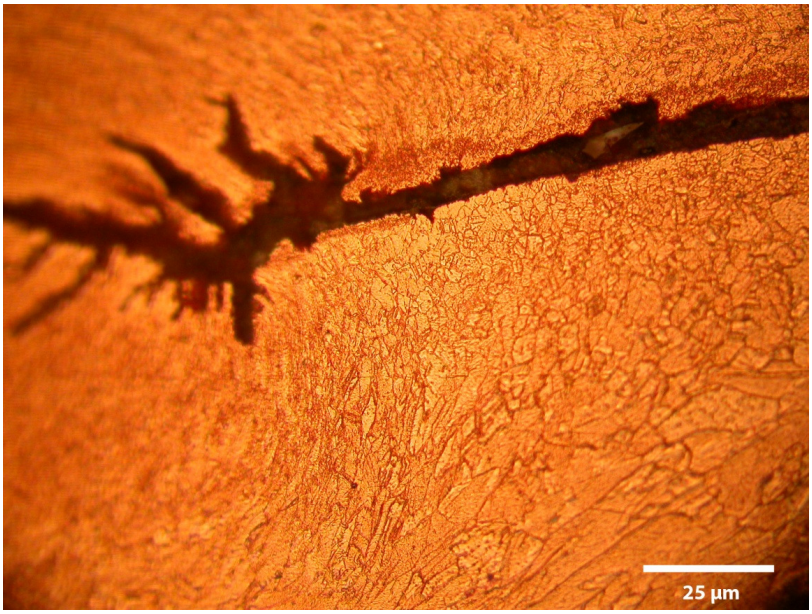

Figure 5.121 GLC2136.

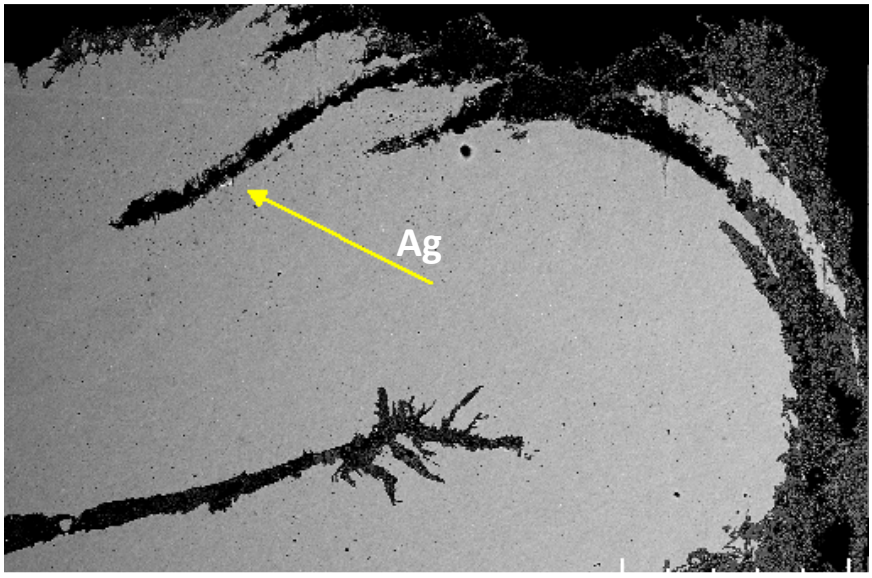

Figure 5.122 Backscattered electron image of copper binding GLC2136 with silver particle.

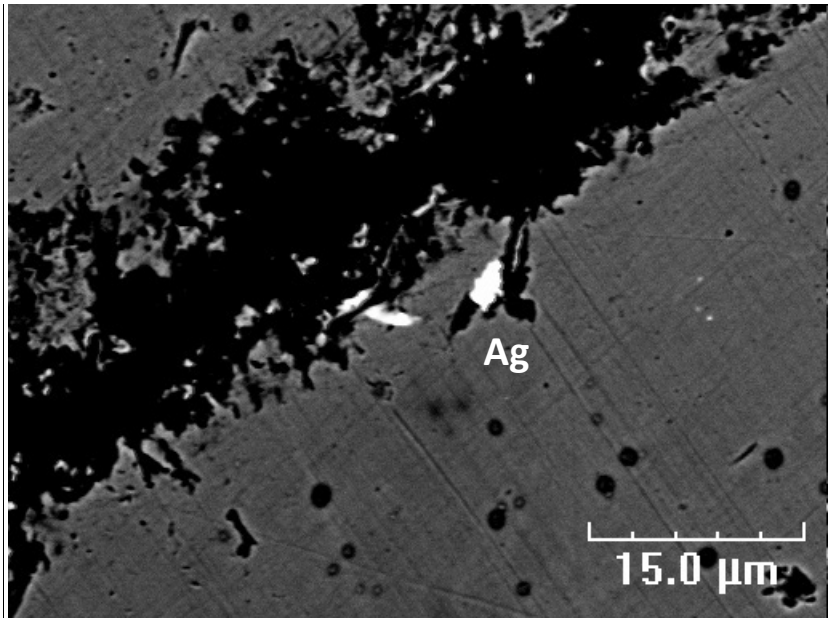

Figure 5.123 Backscattered electron image of copper binding GLC2136 with silver particle at high magnification.

GLC2290 (Fig. 5.124) is also a binding, but made of brass. Its granular structure is heavily deformed and shows abundant strain lines. However, its grain size (17µm) is twice that of the copper binding.

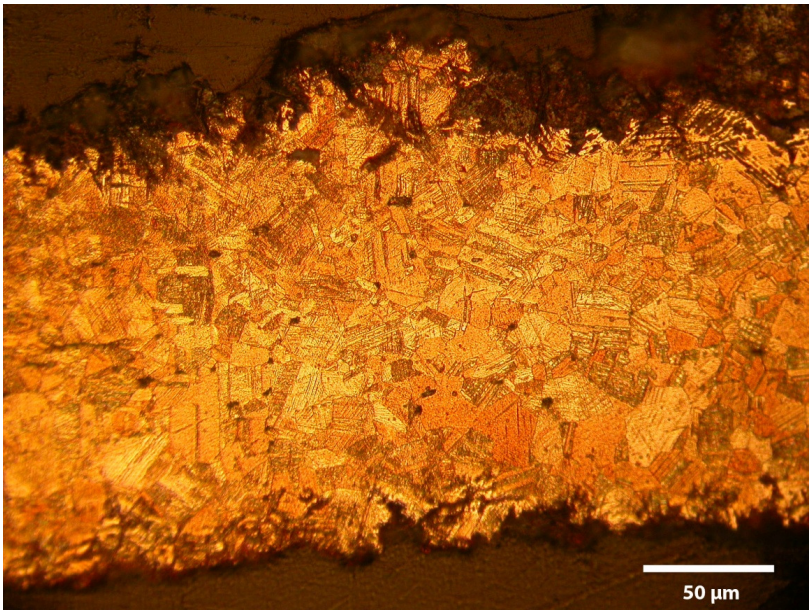

Figure 5.124 GLC2290.

GLC2148 (Fig. 5.125), a brass *lorica segmentata* hinged fitting and a brass strip, GLC2357 (Fig. 5.126) show very similar microstructures, both in morphology and grain size (5µ). The brass strip is plated, however, as indicated by remnants of a silver-tin layer (Fig. 5.127). EDS analysis on the layer gives a composition of 75% silver and 25% tin. Silver-tin alloys that were used as hard solders can be found

in Roman silver objects from Water Newton, Cambridgeshire. In particular, a solder used in one of these objects (Hockwold cup) has a composition of 80% silver and 20% tin (Lang and Hughes 1984: 93). Experiments by Lang and Hughes showed that such silver-tin alloys can produce a good finish colour (Lang and Hughes 1984:91). This observation could be related to the use of the alloy as plating, as it is seen in Figure 5.127.

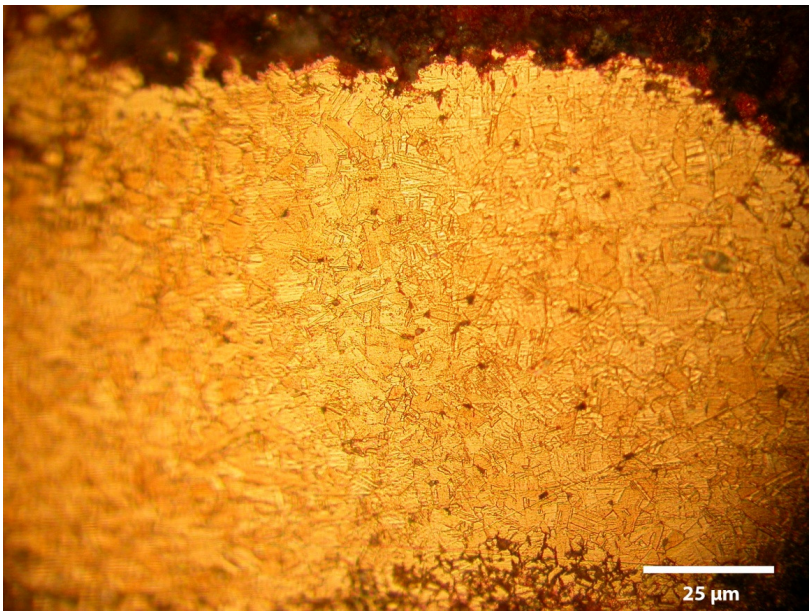

Figure 5.125 GLC2148.

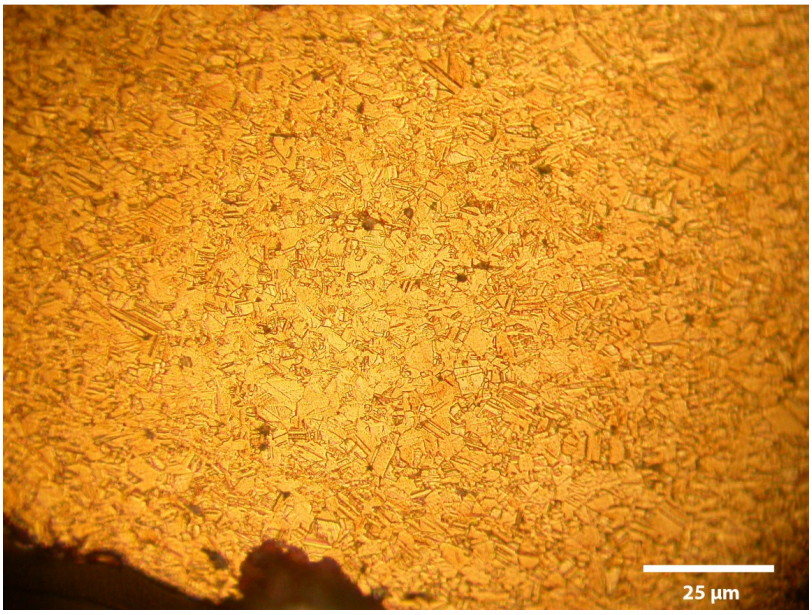

Figure 5.126 GLC2357.

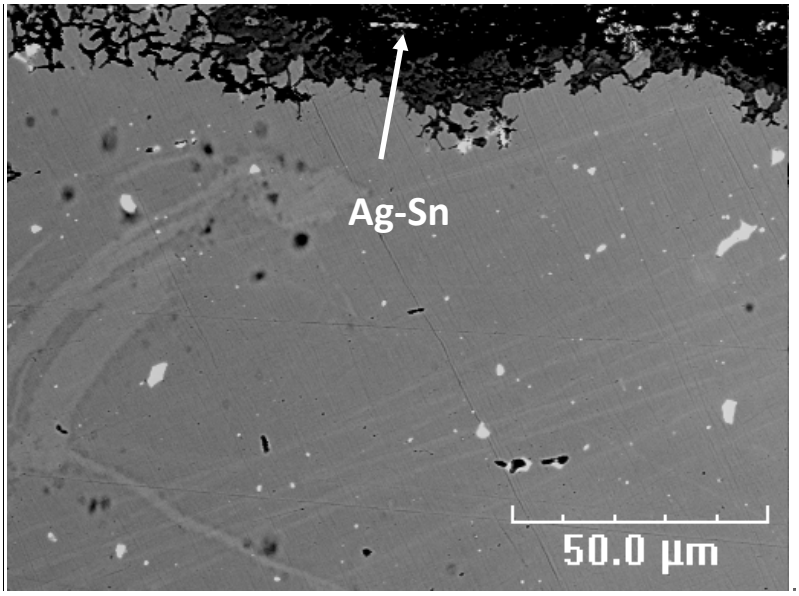

Figure 5.127 Backscattered electron image of a brass strip, GLC2357, as indicated by remains of plating.

GCL2359 (Fig. 5.128) is a brass hinged plate with a very irregular granular microstructure. The grains are very distorted, showing heavy deformation. The horse-harness mounts GLC 2360 (Fig. 5.129) and GLC2361 (Fig. 5.130) are made of low tin gunmetal with very similar zinc and tin contents (Table A2.6). However GLC2360 contains 2.4% lead, as opposed to 0.3% for GLC2361. Both objects have dendritic microstructures that underwent cold-work deformation, but the microstructure of GLC2361 suggests slow cooling, since the microstructure shows almost no traces of the dendritic structure, and resembles a cold-worked granular structure.

Figure 5.128 GLC2359.

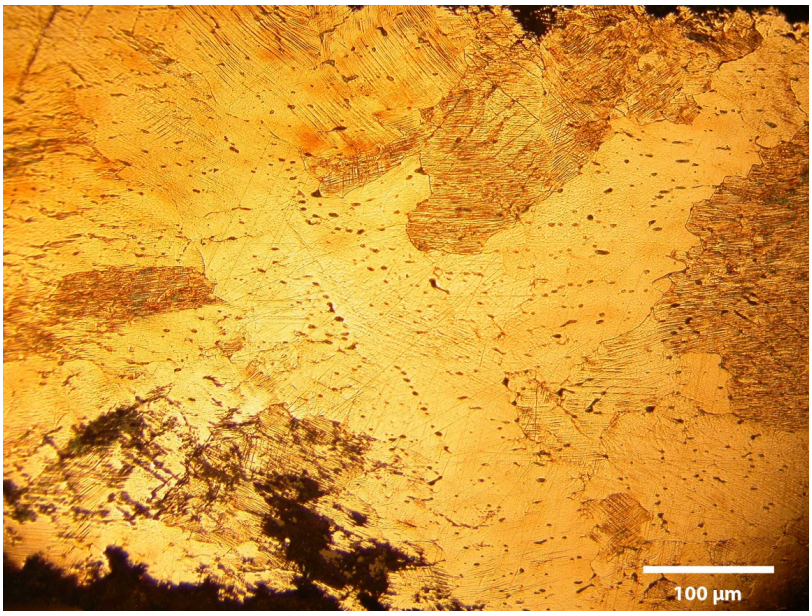

Figure 5.129 GLC2360.

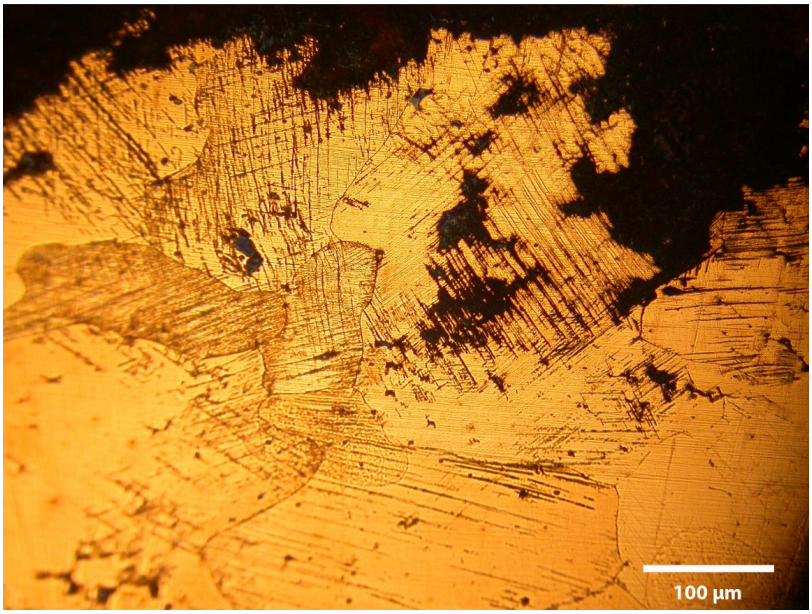

Figure 5.130 GLC2361.

GLC2378 (Fig. 5.131) and GLC2602 (Fig. 5.132) are both made of brass (a *lorica segmentata* hinged plate, and a piece of binding, respectively) with similar compositions, and both show heavily deformed granular microstructures with abundant twinning and strain lines. The hinge plate shows a higher degree of corrosion damage, and a slightly higher degree of deformation. Grain size however, is smaller for the binding (8.5 as opposed to 10.5µm).

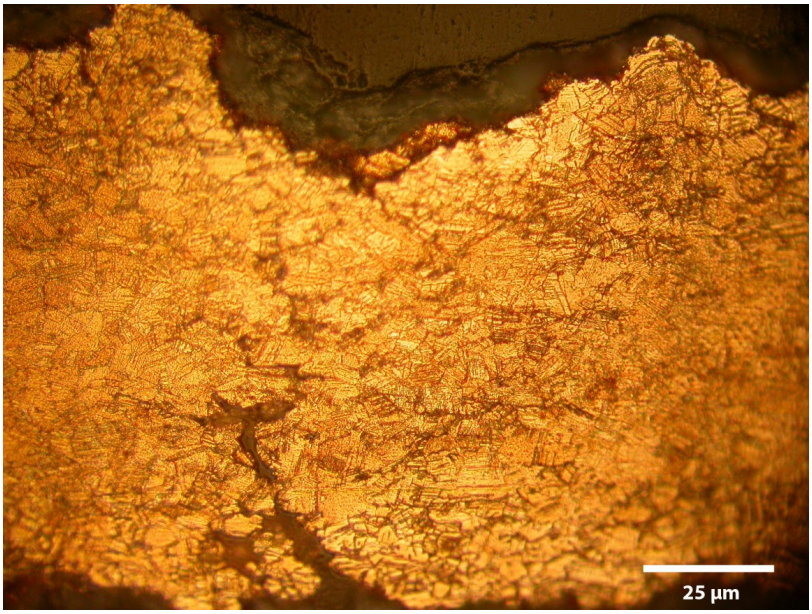

Figure 5.131 GLC2378.

Figure 5.132 GLC2602.

GLC2693 (Fig. 5.133) is a brass horse harness mount similar to GLC2360 and GLC2361, but made of brass, instead of gunmetal (Table A2.6). The microstructure is also constituted by cold-worked dendrites, but in this case they are finer.

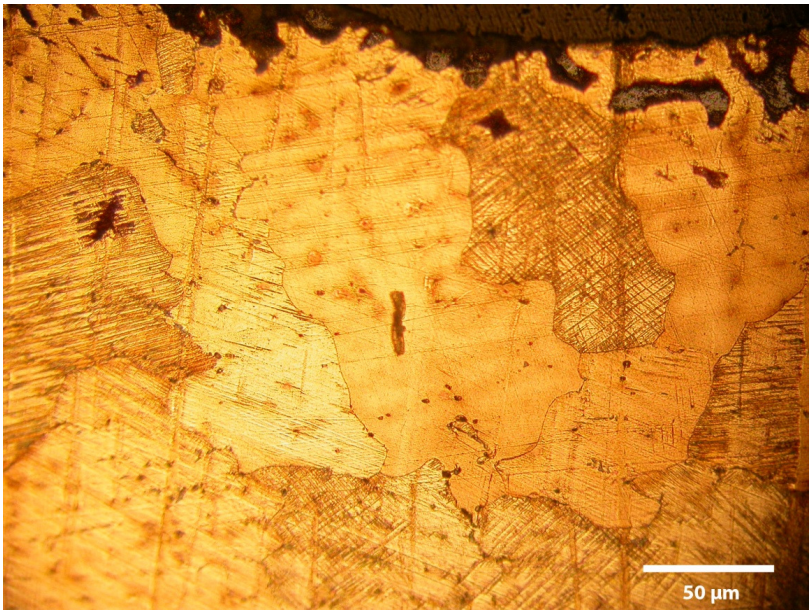

Figure 5.133 GLC2693.

GLC2741 (Fig. 5.134) is a folded strip made of bronze, with very small (7.5µm) twinned grains that suggest recrystallization near the end of the manufacturing period, this aided by the high degree of previous cold-work deformation and annealing cycles.

Figure 5.134 GLC2741.

5.8.4 Surface qualitative analysis of some objects.

It was not possible to take metallographic samples for some objects (some of which were analysed by AAS). However, it was possible to do EDS qualitative analysis on the surfaces of some of them, mainly to identify plating constituents.

GLC125 is a leaded bronze “G” buckle with visible plating (Fig. A1.111). EDS analysis suggested that the plating could be either tinning or an tin-lead alloy (Fig. 5.135). It was not possible to establish if the lead content picked up in the analysis by the detector was due to the plating or a product of the leaded substrate, since the bulk of the object contains 17% lead.

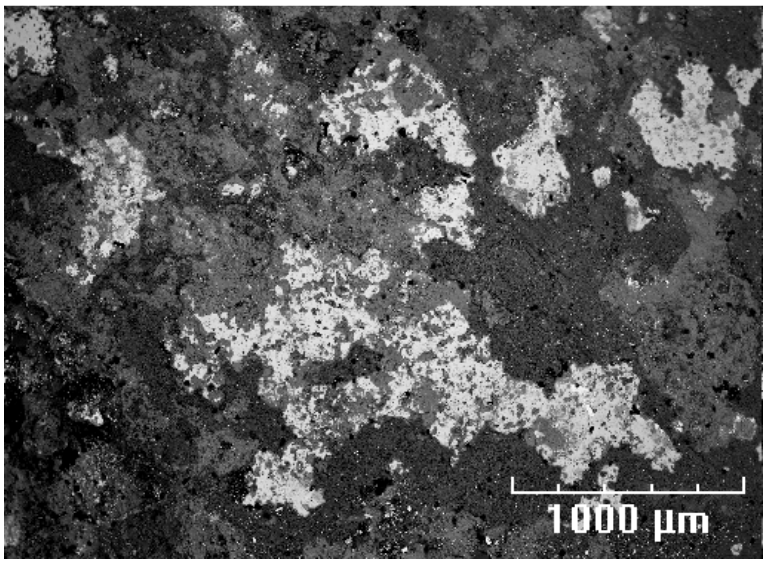

Figure 5.135 Backscattered electron image of the surface of bronze buckle GLC125 with remains of plating.

GLC127 is a brass decorated belt plate with white metal plating. The belt plate is best seen using backscattered electrons (Fig. 5.136) and was tinned, as shown by EDS analysis.

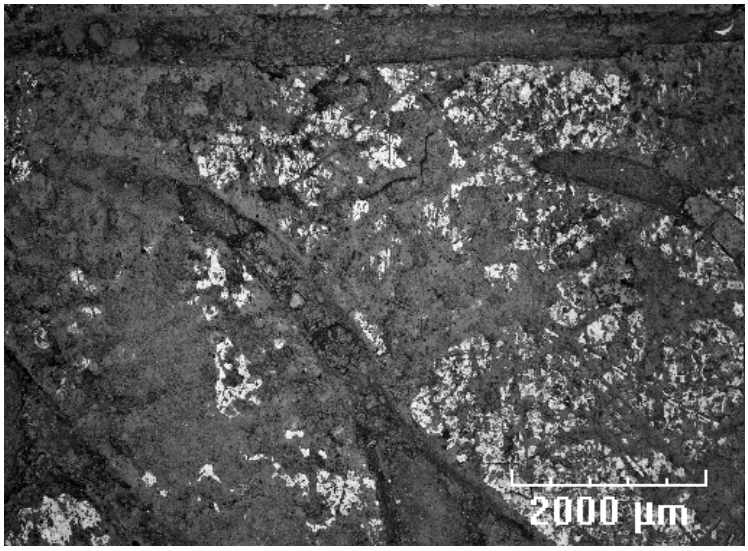

Figure 5.136 Backscattered electron image of the surface o f belt plate GLC127 showing decoration and tin plating.

GLC538 is a gilded un-alloyed copper harness fitting (Fig. A1.119). The gold can be seen as the brightest features in Figure 5.137 and its presence was confirmed by EDS analysis (Fig. 5.138).

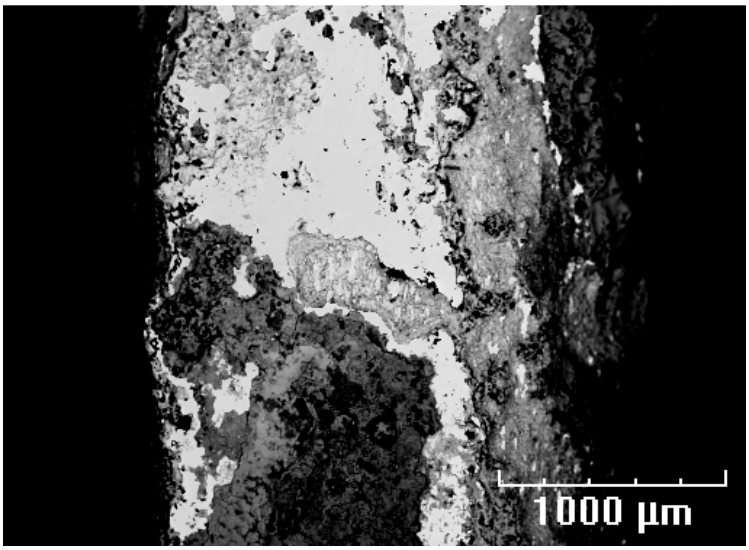

Figure 5.137 Backscattered image of the external surface of GLC538, showing gilding applied (in white).

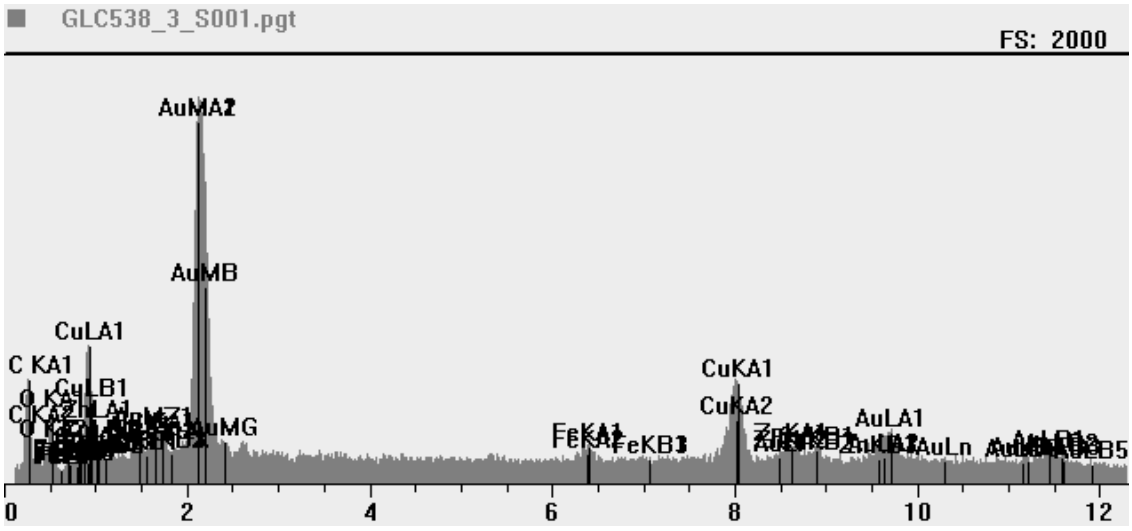

Figure 5.138 Qualitative spectrum of the plating found on GLC538, showing a gold peaks (Au).

GLC2933 is a horse-harness Bishop Type I trifid pendant. It is made of brass and remains of the original decoration are visible on the surface (Fig. A1.182). The surface was observed using backscattered electrons (Fig. 5.139) and qualitative EDS analysis was performed on it. It was found that the plating is made of silver (Fig. 5.140).

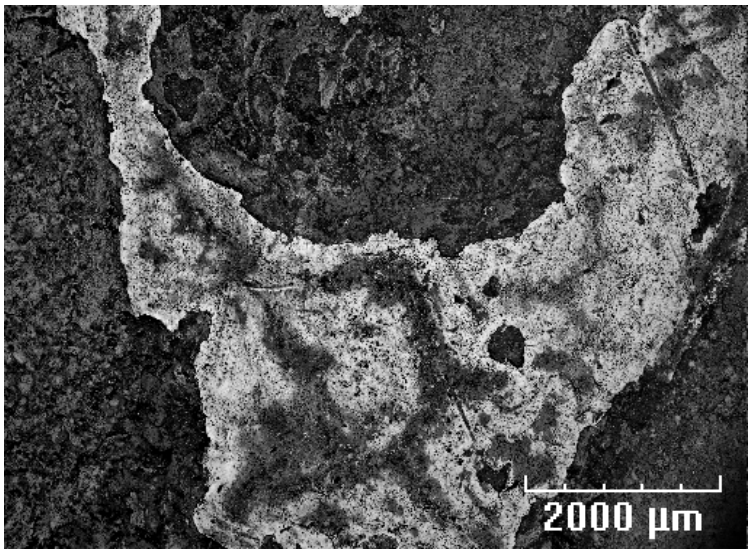

Figure 5.139 Backscattered electron image showing silver plating on the surface of brass pendant GLC2933.

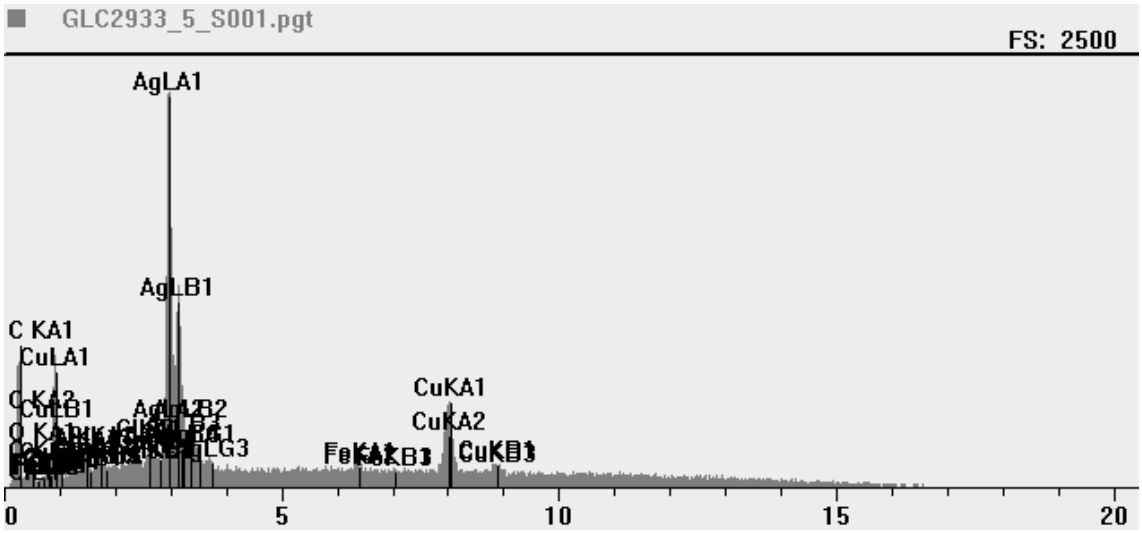

Figure 5.140 EDS spectrum of analysis taken on the remaining plating of GLC2933 showing a silver peak (Ag).

GLC2943 is an un-alloyed copper dagger frog, also with visible plating on the surface (Fig. A1.185). Closer observation using SEM-EDS reveals that the applied plating (Fig. 5.141) is silver, as the EDS spectrum shows (Fig. 5.142).

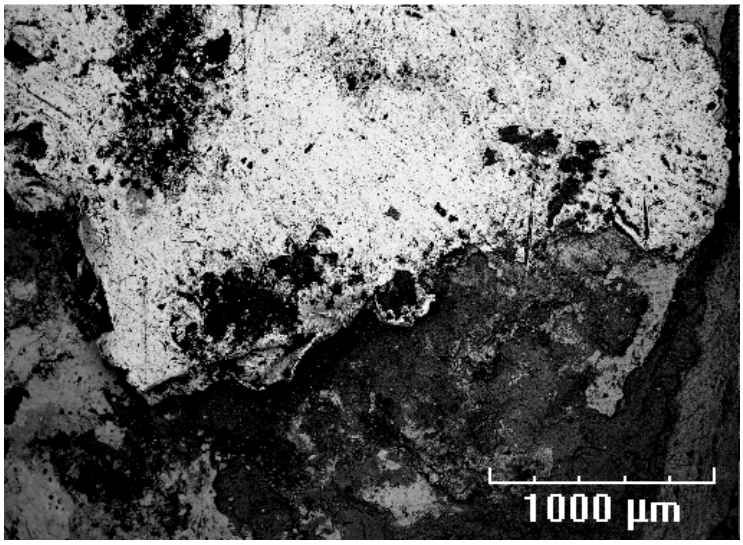

Figure 5.141 Backscattered electron image of the surface GLC2943, showing remains of the silver plating.

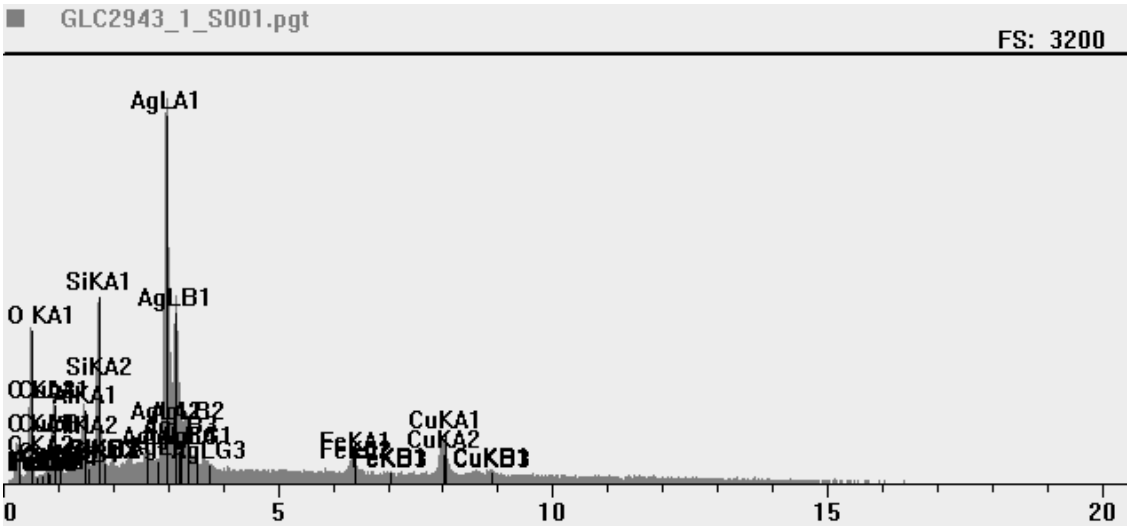

Figure 5.142 EDS spectrum of plating seen on GLC2943, showing a prominent silver peak (Ag).

5.8.3 Grain Size

Of all the metallographic samples obtained from the site of Kingsholm that show granular microstructures (Fig. 5.143), two artefact types occur more than once: *lorica segmentata* fittings and metal sheet/plate fragments. In the case of the *lorica* fittings (six samples analysed), with the exception of GLC1376, the grain size is noticeably smaller and shows a smaller spread when compared to that of the metal sheet/plate fragments analysed (eight in total). A smaller grain size gives greater strength and hardness to the material, and the smaller spread suggests a higher degree of control in the fabrication of the *lorica segmentata* fittings.

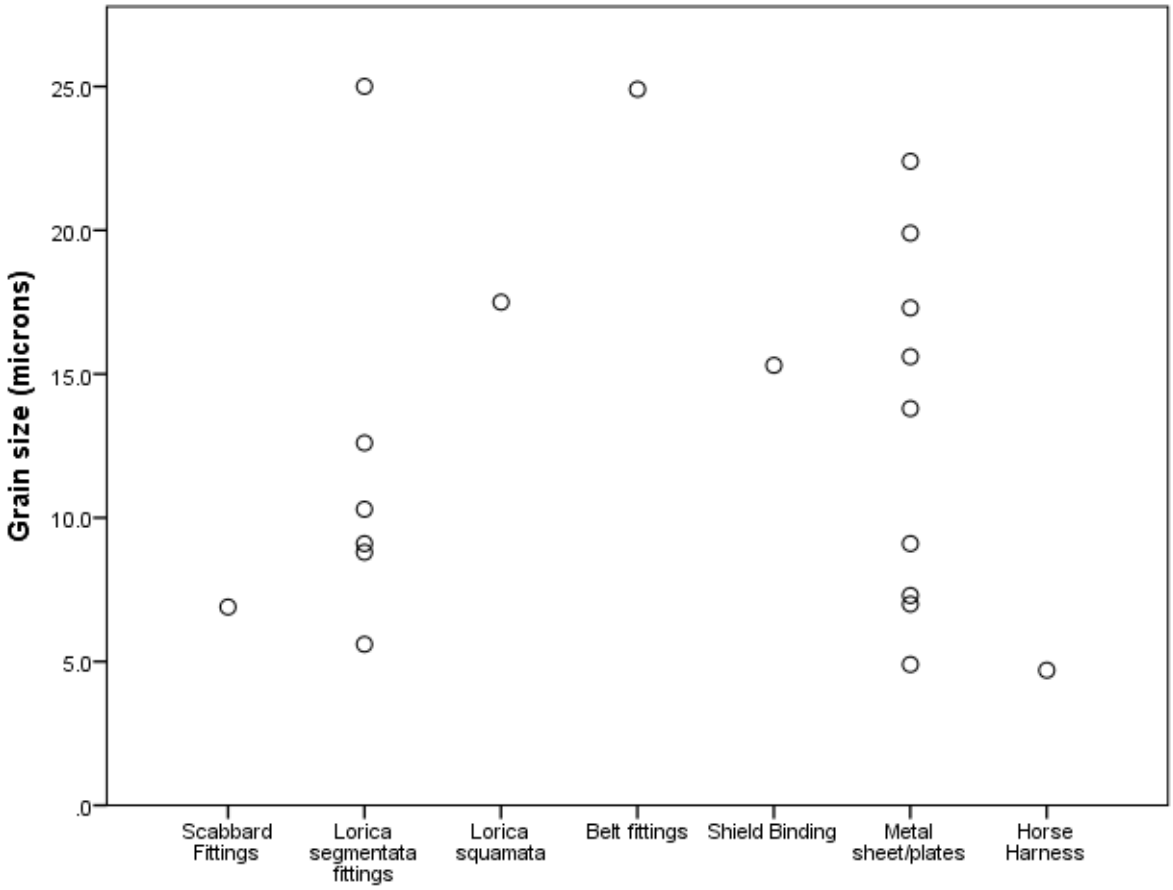

Figure 5.143 Kingsholm: Grain size by object type. Five of the types are represented by only one sample.

5.9 Kalkriese

5.9.1 AAS results (see Table A2.7)

A total of 31 samples were analysed by AAS including trace elements (See Appendix 2 for composition and sample names to which this chapter refers).

5.9.2 Alloy type

The assemblage is heavily dominated by shield binding fragments (Fig. 5.144), of which all but one are made of brass, this is composed of unalloyed copper (this material represents 11% of the analysed assemblage: 7% unleaded and 4% leaded). The other brasses are a socket, and the seven samples of *litui* analysed, of which three were found to belong to the same object or are at least made from the same alloy.

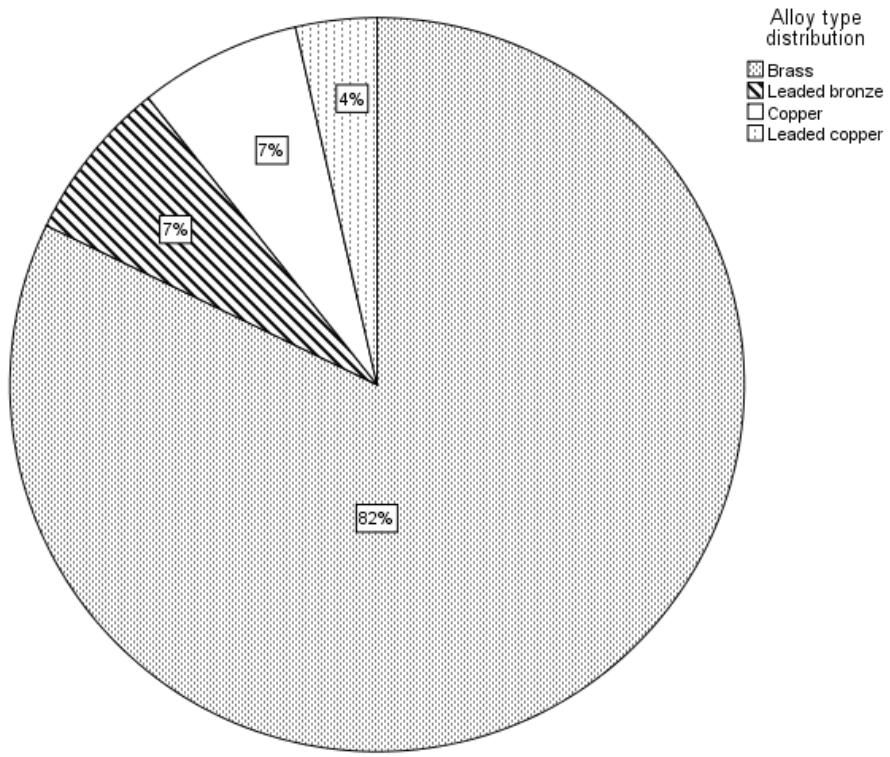

Figure 5.144 Distribution of alloy type in the objects from Kalkriese.

5.9.3 Four *lituus* fragments

Four *lituus* fragments, K10282, K10107, K10412 and K10413, were found to be part of the same object, or at least the same alloy. The copper and zinc contents were similar to those of other brasses in the assemblage and the trace element values were extremely close amongst the four fragments. These samples can therefore be considered part of the same object (Table 5.2). This was confirmed by metallographic observation, where very similar morphology and grain size were observed among the four samples.

	%Cu	%Pb	%Sn	%Zn	%Ag	%Fe	%Ni	%Co	%Mn	%Sb	%As
K10282x	80.8	0.41	0.32	18.24	0.024	0.095	0.101	<0.005	<0.003	0.045	<0.06
K10107x	79.5	0.43	0.22	19.52	0.026	0.096	0.104	<0.006	0.004	0.063	<0.08
K10412x	79.0	**0.43**	0.44	19.92	0.024	0.094	0.103	<0.005	0.001	0.038	<0.05
K10413x	79.0	0.44	0.50	19.82	0.028	0.088	0.101	0.007	<0.0016	0.034	<0.11
Average	**79.6**	**0.43**	**0.37**	**19.37**	**0.026**	**0.093**	**0.102**	**0.007**	**0.0025**	**0.045**	**<0.05**
RSD	1.07	2.80	33.36	4.00	7.51	3.85	1.47		84.85	28.52	

Table 5.2 AAS results for fragments of the same *lituus*.

5.9.4 Dezincification

Most of the sampled objects from Kalkriese had lost up to 30% of the original zinc content due to corrosion penetrating deep into the sample. Dezincification, a phenomenon analogous to destannification in bronzes, is the preferential corrosion of zinc over copper. In this way part of the zinc content of the sample is lost. However, by using EDS and metallographic analysis, it was possible to determine the original zinc composition by analysing metal with the original composition. Dezincification did not affect the concentrations of the trace elements associated with the copper, such as arsenic, antimony, nickel, cobalt, and silver.

The 22 brasses from Kalkriese follow a distribution close to normality and have a mean at 20.8% (Fig. 5.145). A sheet fragment was made of bronze, while the leaded bronzes correspond to a belt buckle (K5610), and a helmet knob (K22373).

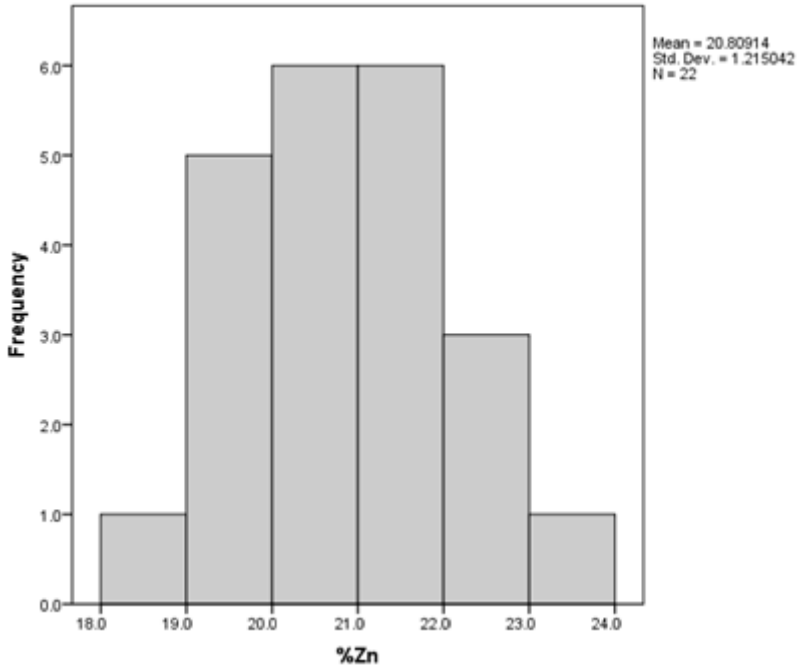

Figure 5.145 Zinc distribution in the brass objects from Kalkriese.

In the case of antimony and arsenic, which are associated with the copper, there is a positive correlation suggested (R^2= 0.57) (Fig. 5.146). However, since the precision for arsenic is not high in AAS and the arsenic levels for some samples are close to the limit of detection, the faint correlation could be a product of the technique and not real. The two groups, separated by arsenic content (see Fig. 5.146) are also likely to be produced by the effect of both the low precision of arsenic measurements by flame AAS and the proximity to the limit of detection for all the samples. The brass shield binding and *lituus* fragments, and bronzes are represented in both groups: separation of the two groups as seen in Figure 5.146 does not seem due to alloy type or object type either.

However, more samples made of alloys other than brass would be necessary to associate or disassociate the two groups with an alloy type.

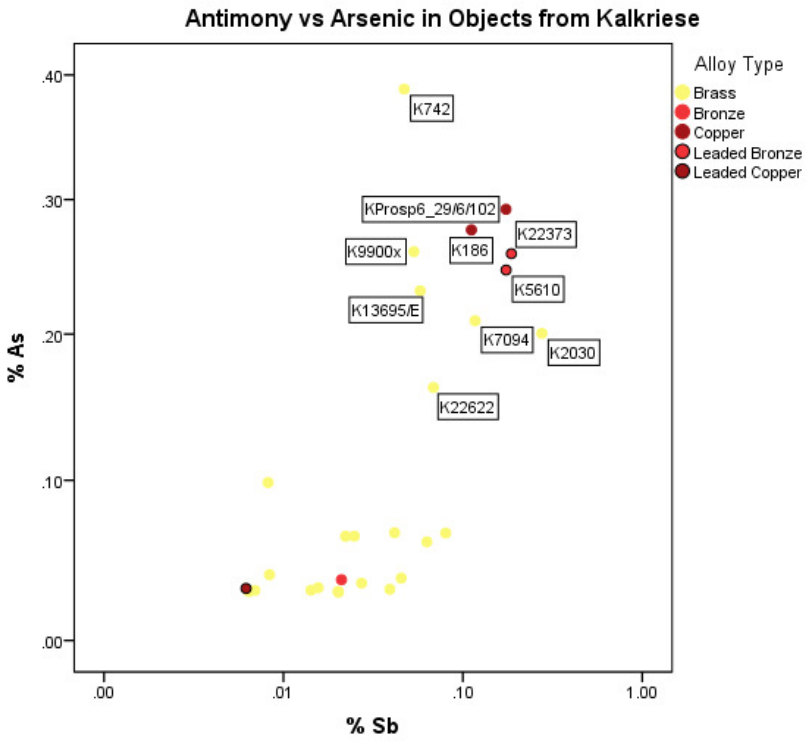

Figure 5.146 Kalkriese. Antimony v. arsenic bivariate plot, with both elements re-scaled to the copper.

5.9. 5 Metallography

Most of the micrographs of the objects from Kalkriese belong to samples with a granular structure, since the assemblage is dominated by objects made from sheet metal (shield binding, *litui*). All the shield binding fragments analysed metallographically are primary brasses, except K13695E, which contains approximately 12% zinc and 0.5% tin. The only bronze shield binding in the assemblage was not sampled for metallography.

All the shield binding fragments show granular structures with distorted twinned grains, and show corrosion products covering both surfaces of the cross sections. However, they can be roughly divided into two groups according to grain size. In the first group there are four objects with grain sizes ranging from 23 to 28µm: K742 (Fig. 5.147), K2002 (Fig. 5.148), K13695E (Fig. 5.149) and K22622 (Fig. 5.150). Three of the bindings from the first group, K742, K13695E and K22622, are also members of the group defined by higher arsenic and antimony content (Fig. 5.146).

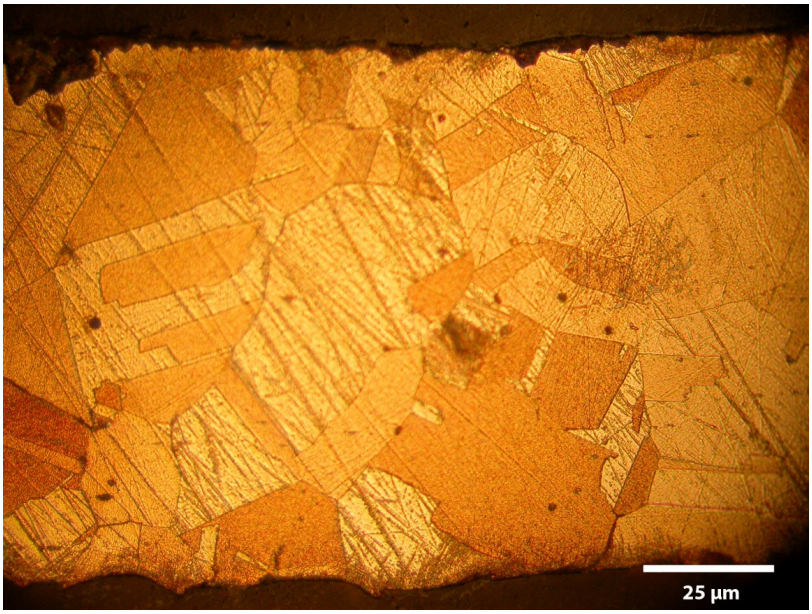

Figure 5.147 K742.

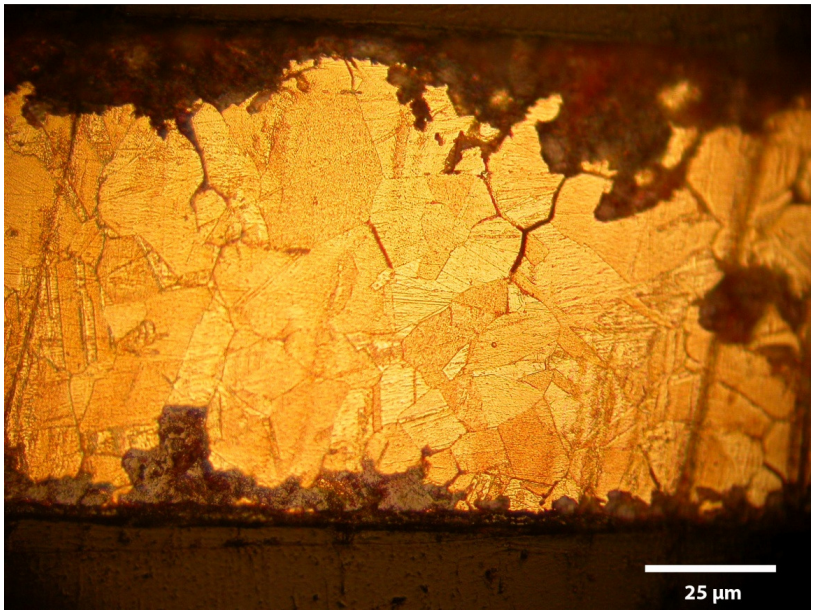

Figure 5.148 K2002.

Figure 5.149 K13695E.

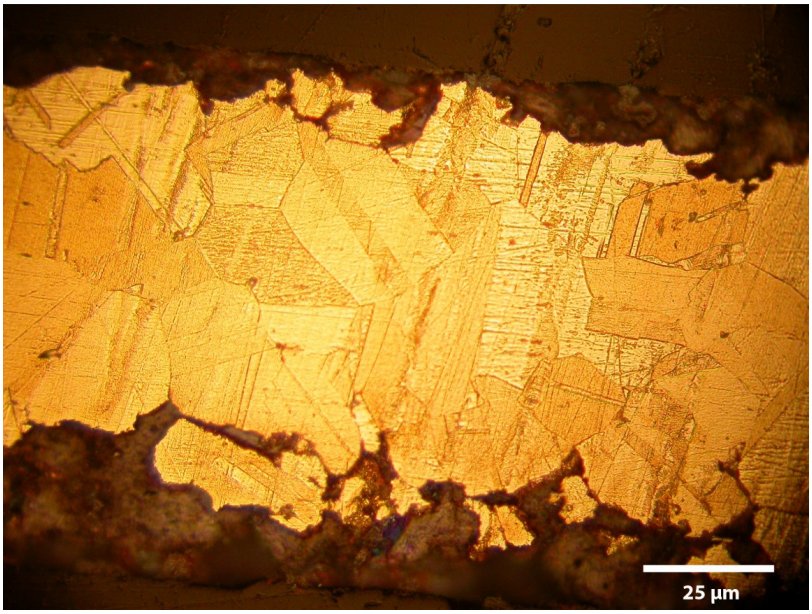

Figure 5.150 K22622.

The remaining brass shield binding fragments show grain sizes from 34 to 43 µm: K3223 (Fig. 5.151), K3797 (Fig. 5.152), K10550 (Fig. 5.153), K11816 (Fig. 5.154). One of the bindings, K11816 shows two seemingly trans-granular fractures running longitudinally to the cross section. These fractures could be stress related corrosion cracking, produced after deposition, as it was favoured by residual stresses in the direction of deformation.

Figure 5.151 K3223.

Figure 5.152 K3797.

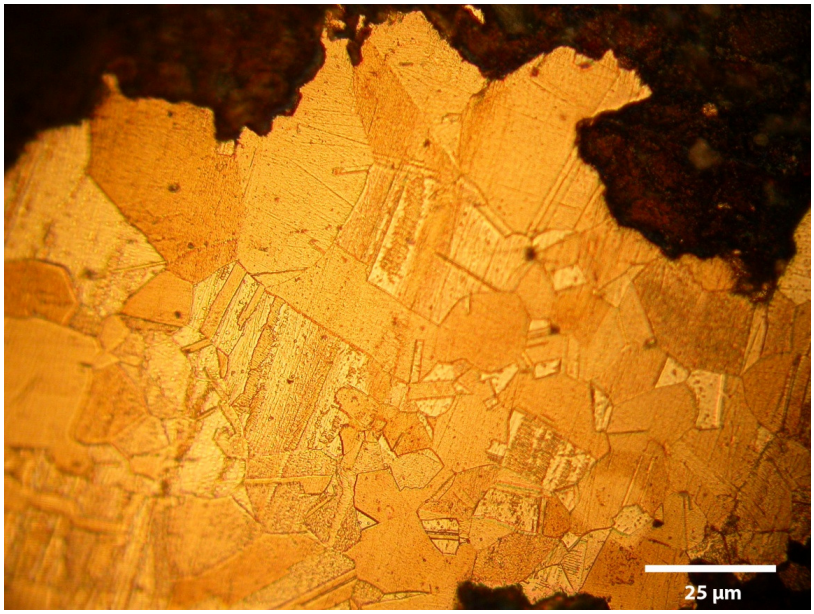

Figure 5.153 K10550.

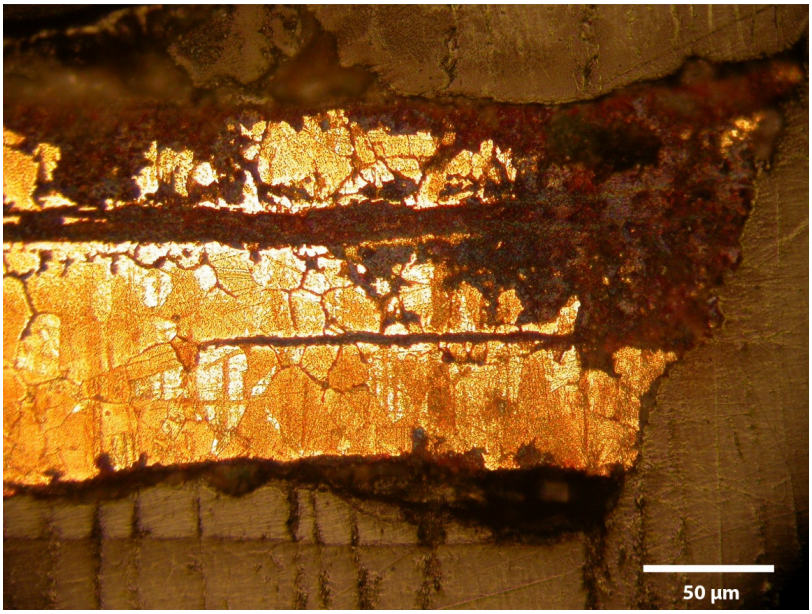

Figure 5.154 K11816.

There are two sheet fragments in the assemblage: one is made of un-alloyed copper, K186 (Fig. 5.155), and the other of bronze, K33801 (Fig. 5.156). The copper fragment presents more distorted grains, which can be seen elongated in the direction of deformation. The bronze fragment has larger grains (25µm) with broader twins, and show less deformation.

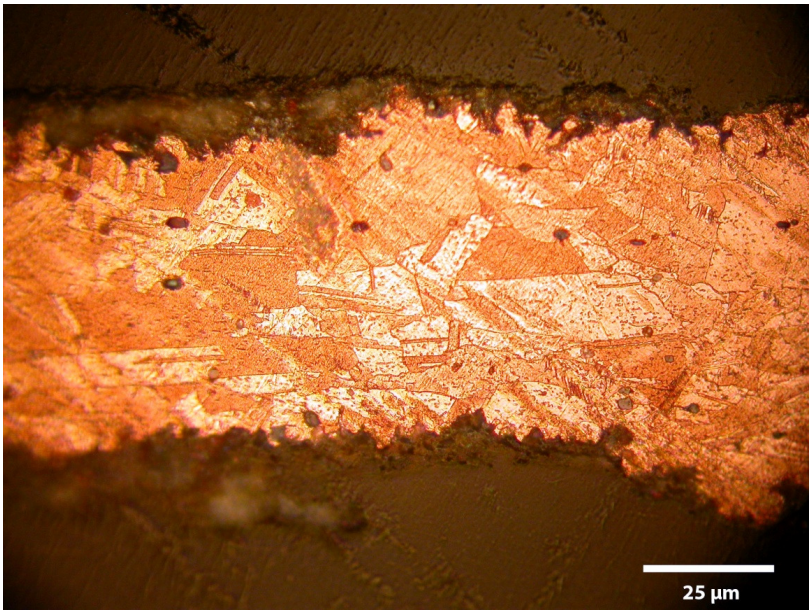

Figure 5.155 K186.

Figure 5.156 K33801.

The three fragments that belong to the same *lituus*, K10282 (Fig. 5.157), K10412 (Fig. 5.158), and K10413 (Fig. 5.159) show a very similar microstructure. The grains are irregular and twinned, and have relatively large grain sizes: 48, 40 and 42µm. The object is a 19.5% zinc brass and has 0.4% lead, which is enough to appear as globules dispersed randomly in the sample. The remaining metal is enveloped in a thick corrosion layer.

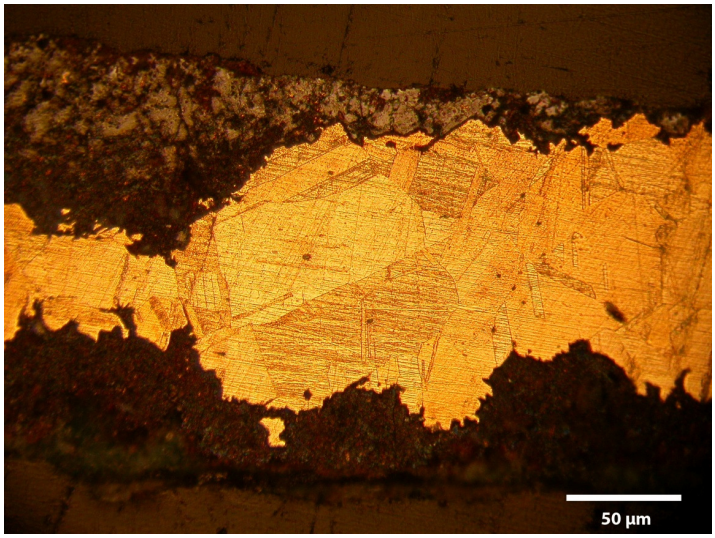

Figure 5.157 K10282.

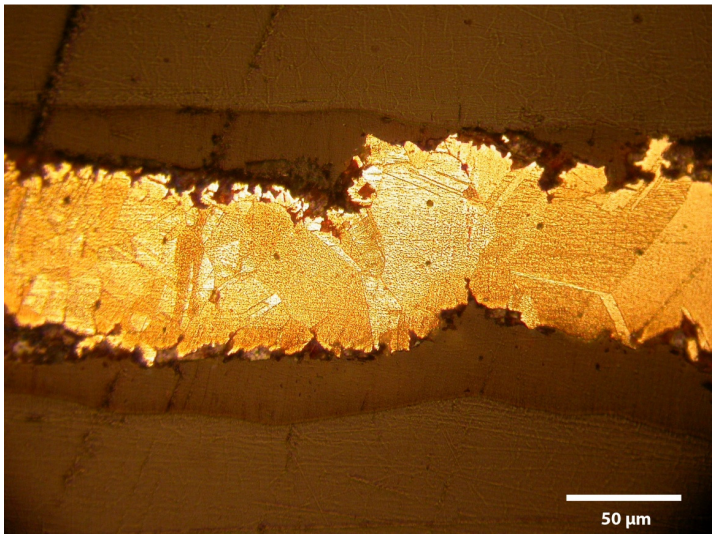

Figure 5.158 K10412.

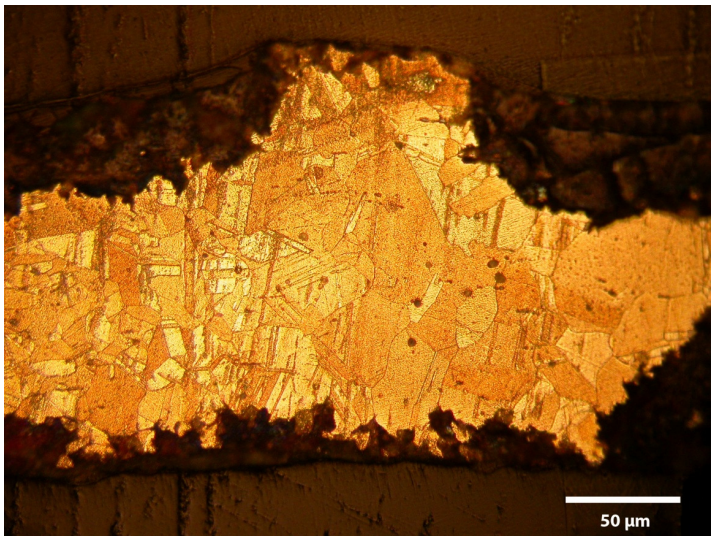

Figure 5.159 K10413.

Two other *lituus* fragments, K2030 (Fig. 5.160), and K10597 (Fig. 5.161), also made of brass, show microstructures with slightly greater deformation. Grain size is different between these two samples, 28 and 17µm, and is considerably smaller than that of the three *lituus* fragments mentioned above.

Figure 5.160 K2030.

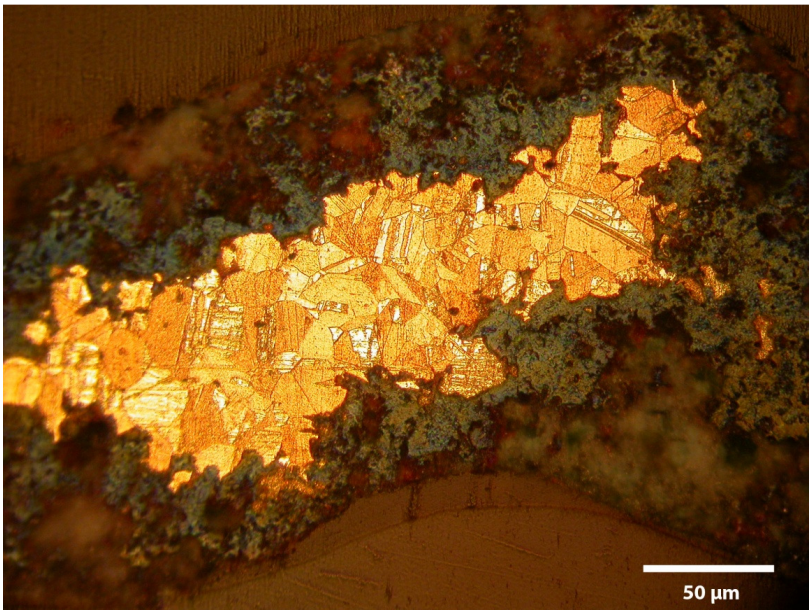

Figure 5.161 K10597.

5.9. 6 Grain size comparison

The shield binding fragments generally have smaller grains than the *litui*, ranging from 18 to 43µm in size, but most of them are between 25µm and 35µm (Fig. 5.162). Smallest in grain size are the two fragments of metal sheet of different alloys, bronze and copper, with values of 25 and 15µm, respectively.

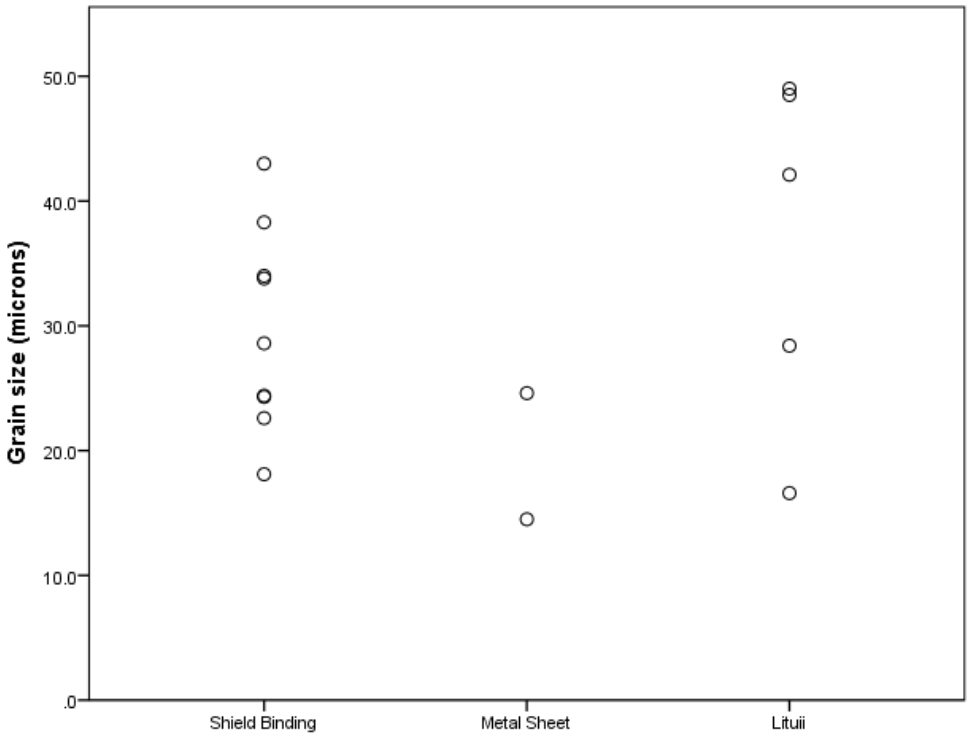

Figure 5.162 Distribution of grain size by type of object, Kalkriese.

5.10 All Sites

5.10. 1 Alloy type

The distribution by alloy type for all sites (Fig. 5.163) shows that 51% of the total objects are made of brass (of which 2% are leaded), 20% made of bronze (75% of which are leaded), 23% made of gunmetal and 6% of un-alloyed copper. Most of the leaded bronzes, however, are of post-2nd century date.

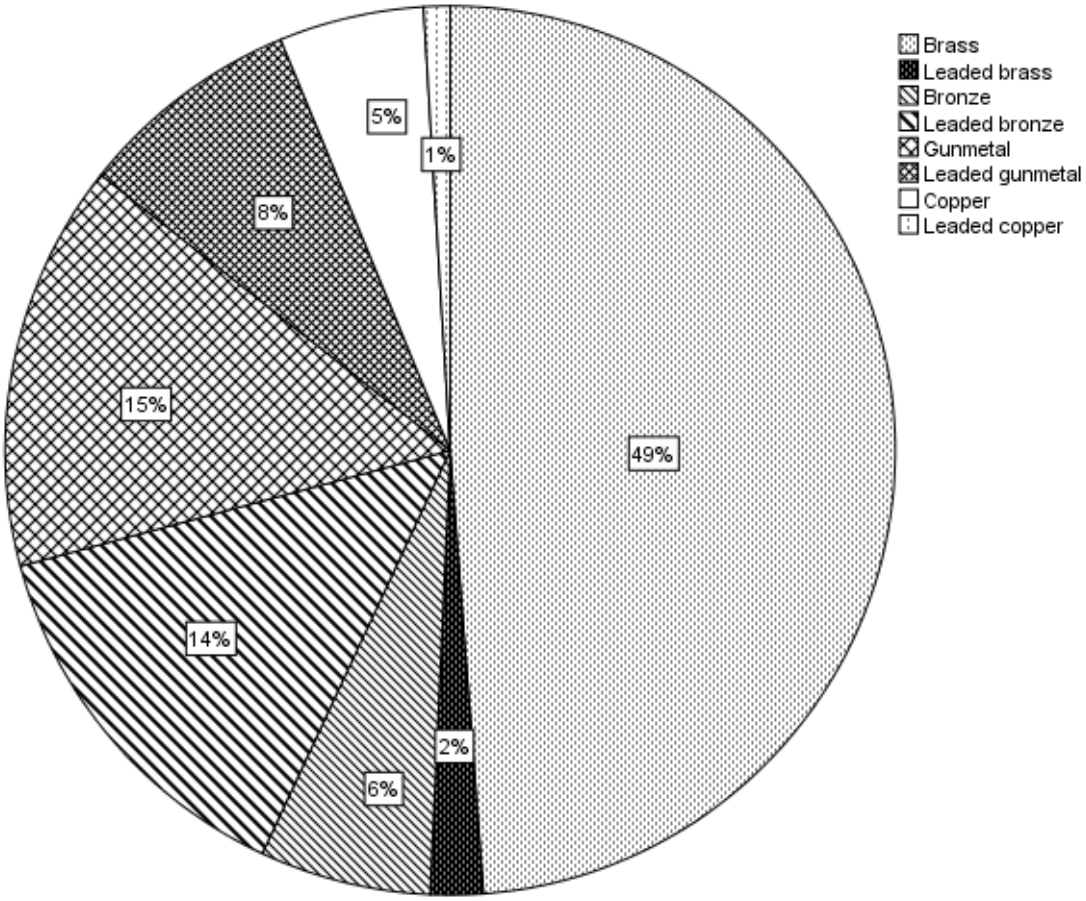

Figure 5.163 Distribution of alloy type for all sites.

The distribution of zinc across all the sites considered for this thesis range from quantities below the limit of detection for AAS to 25%. However, the zinc contents are concentrated in three ranges: 20% to 22%, corresponding to primary brass; 17% to 19%, corresponding to secondary brass; and 8% to 10%, associated with gunmetals (Fig. 5.164).

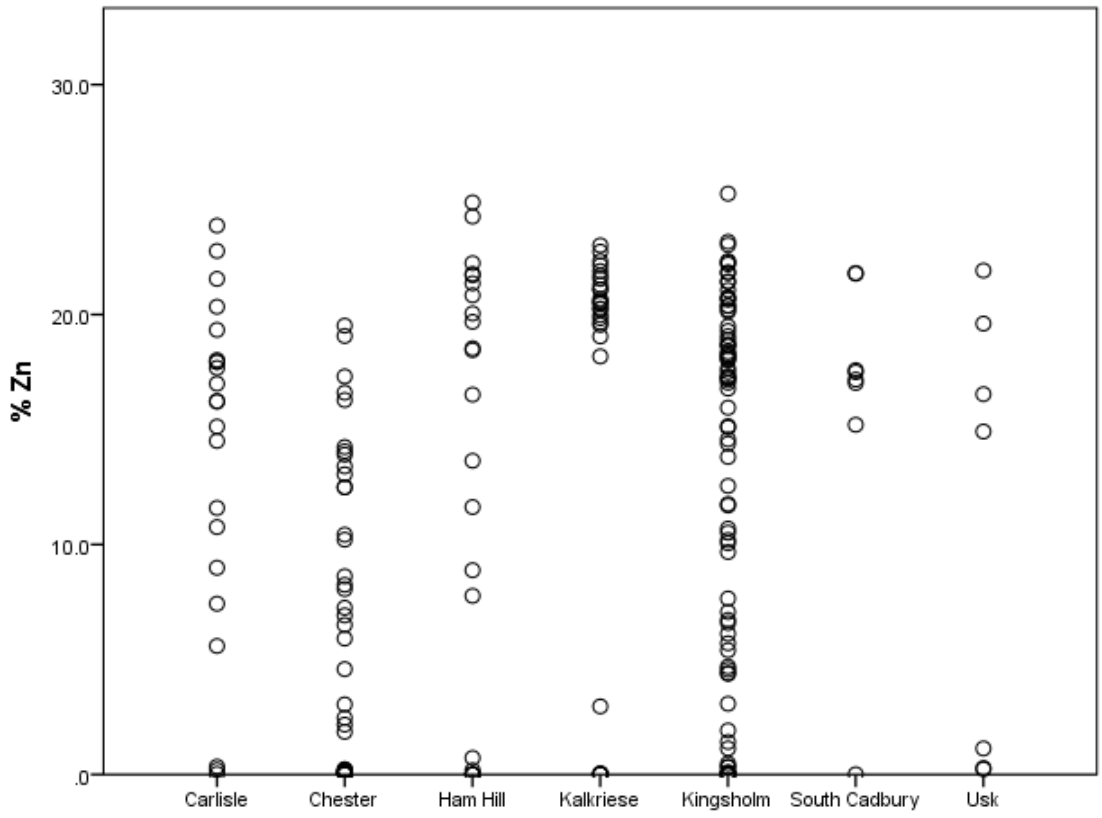

Figure 5.164 Dotplot showing distribution of zinc for all sites.

A bivariate plot of tin against zinc shows an inverse correlation, long noticed by Craddock in other Roman copper-alloy assemblages (1978). Once above the limit of detection, the content of zinc increases with the decrease of tin (Fig. 5.166). This behaviour depends on the time variable, as the content of tin tends to increase at expense of the zinc over time (Fig. 5.167).

Tin shows a bimodal distribution for all the sites before the third century (Fig. 5.165) with a broad peak ranging from below the limit of detection to about 4%. There is a second smaller and thinner peak at about 8%. For later periods the tin content in bronzes is frequently higher than 10% (Fig. 5.167).

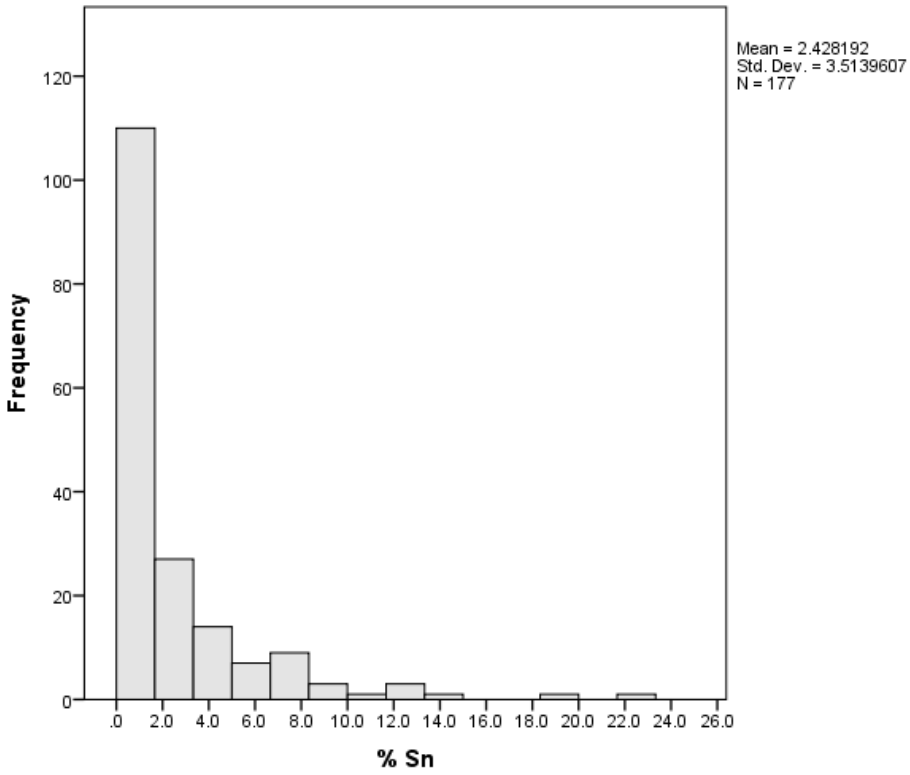

Figure 5.165 Tin distribution for all sites, first and second centuries.

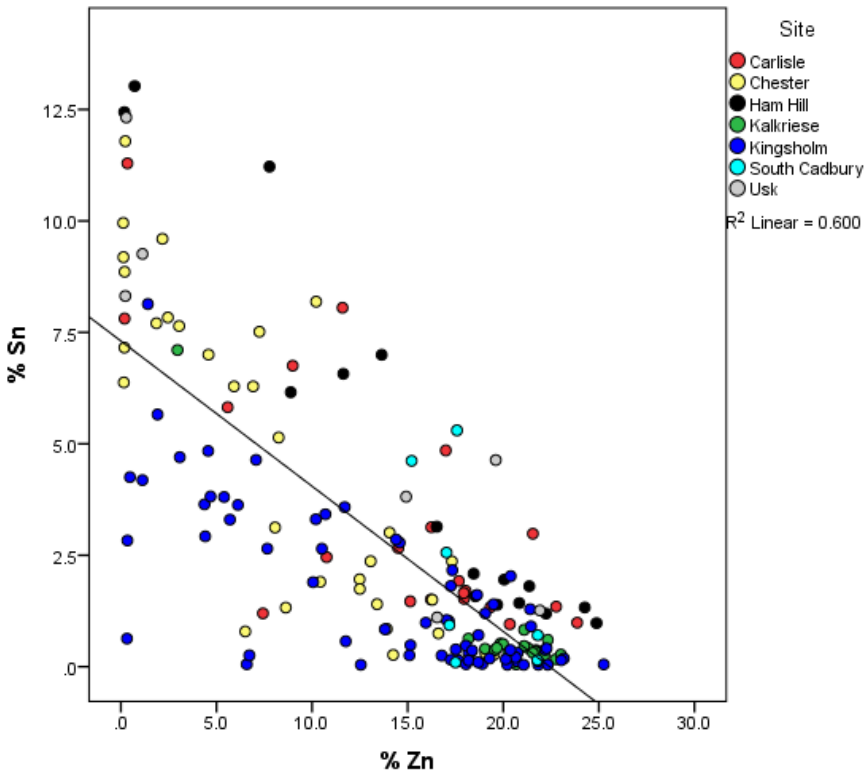

Figure 5.166 Bivariate plot of zinc v. tin of samples analysed, colour coded by site.

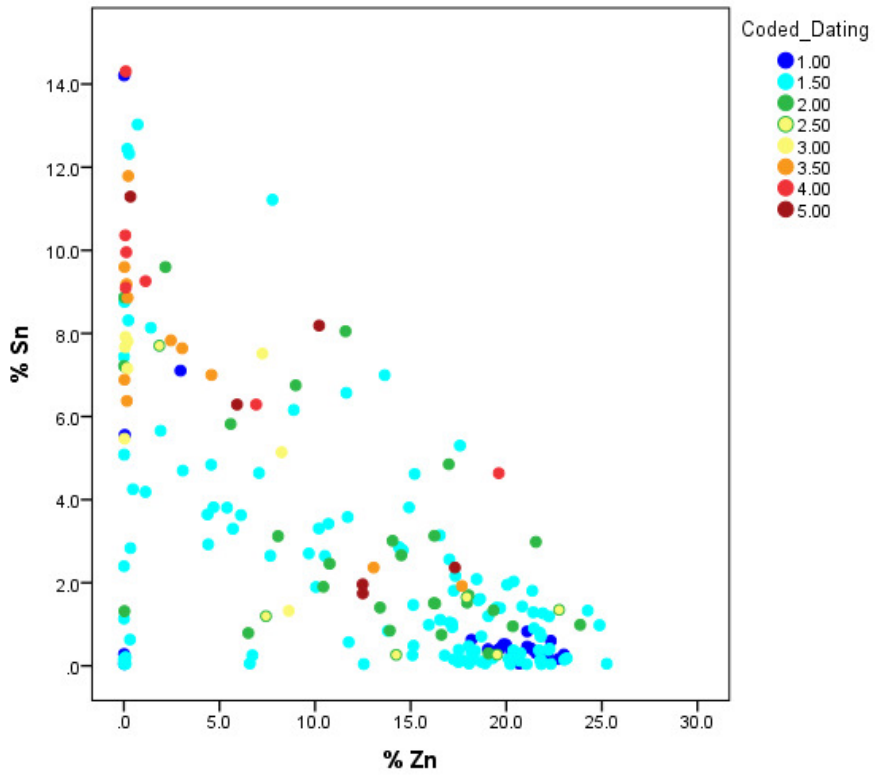

Figure 5.167 Bivariate plot of zinc v. tin of samples analysed, colour coded by time period.

5.10.2 Trace elements

The AAS data obtained for some trace elements: silver, iron, nickel, cobalt, arsenic and antimony, were re-scaled to the copper, since they are normally associated with this metal (Table 5.3). Re-scaling was performed to account for absolute trace element differences due to different copper contents between samples. In this way, the samples can be compared with each other, regardless of their zinc and tin contents. These data were the basis for bivariate plots and multivariate analysis plots that involved different sites.

		%Ag	%Fe	%Ni	%Co	%Sb	%As
Cadbury Castle	Min	0.037	0.022	0.002	0.005	0.06	0.11
	Max	0.166	0.394	0.027	0.651	0.39	1.11
	Mean	0.099	0.298	0.010	0.092	0.15	0.55
	St.Dev.	0.037	0.143	0.010	0.226	0.11	0.31
Ham Hill	Min	0.057	0.055	0.003	0.002	0.03	0.07
	Max	0.400	1.486	0.082	0.212	0.54	1.99
	Mean	0.137	0.365	0.035	0.027	0.16	0.33
	St.Dev.	0.091	0.385	0.022	0.044	0.14	0.42
Usk	Min	0.035	0.146	0.006	0.009	0.08	0.03
	Max	0.050	0.550	0.049	0.469	0.13	0.37
	Mean	0.043	0.303	0.018	0.108	0.11	0.23
	St.Dev.	0.006	0.182	0.018	0.202	0.03	0.14
Carlisle	Min	0.035	0.078	0.005	0.008	0.03	0.03
	Max	0.108	0.423	0.050	0.386	0.29	0.51
	Mean	0.054	0.269	0.017	0.040	0.11	0.19
	St.Dev.	0.018	0.100	0.011	0.082	0.07	0.16
Chester	Min	0.034	0.007	0.007	0.003	0.07	0.03
	Max	0.132	4.084	0.044	0.193	0.24	0.36
	Mean	0.061	0.554	0.019	0.033	0.14	0.12
	St.Dev.	0.027	1.008	0.009	0.061	0.06	0.11
Kingsholm	Min	0.001	0.006	0.001	0.002	0.01	0.02
	Max	0.390	2.488	0.276	0.238	0.49	1.24
	Mean	0.066	0.349	0.039	0.013	0.11	0.15
	St.Dev.	0.052	0.376	0.058	0.036	0.11	0.18
Kalkriese	Min	0.011	0.006	0.009	0.002	0.01	0.02
	Max	0.194	0.665	0.102	0.018	0.22	0.31
	Mean	0.056	0.166	0.038	0.005	0.05	0.10
	St.Dev.	0.042	0.130	0.026	0.004	0.06	0.09

Table 5.3 AAS results for trace elements, rescaled to the copper.

Silver (Ag) tends to be concentrated at 0.05% for most sites, but it is higher for Ham Hill and South Cadbury, but slightly lower in the case of the equipment from Kalkriese (Fig. 5.168).

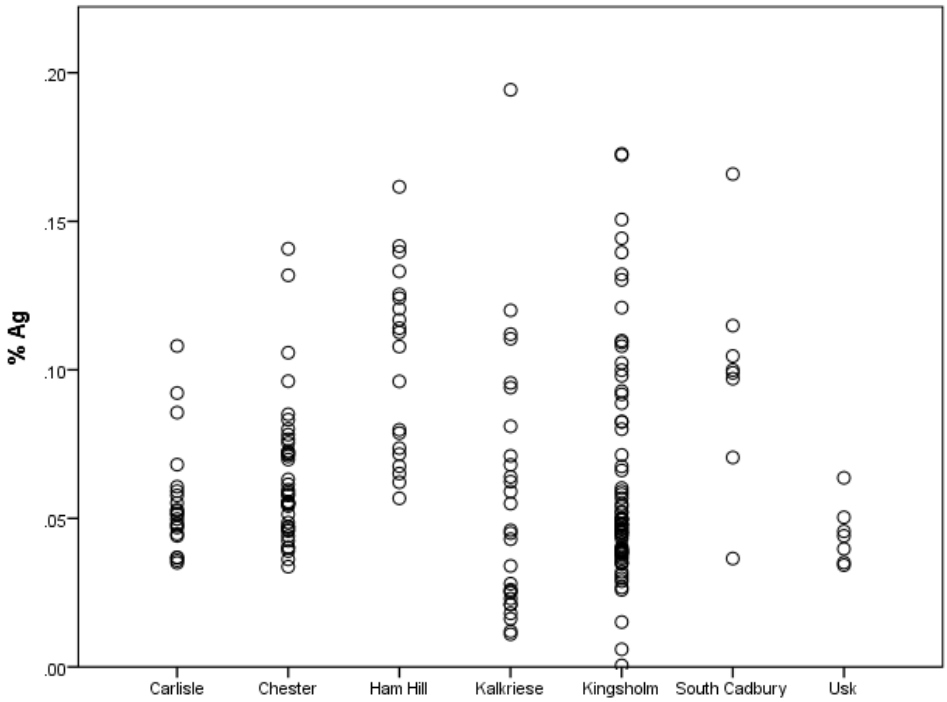

Figure 5.168 Dotplot showing distribution for silver (re-scaled to the copper) for all sites.

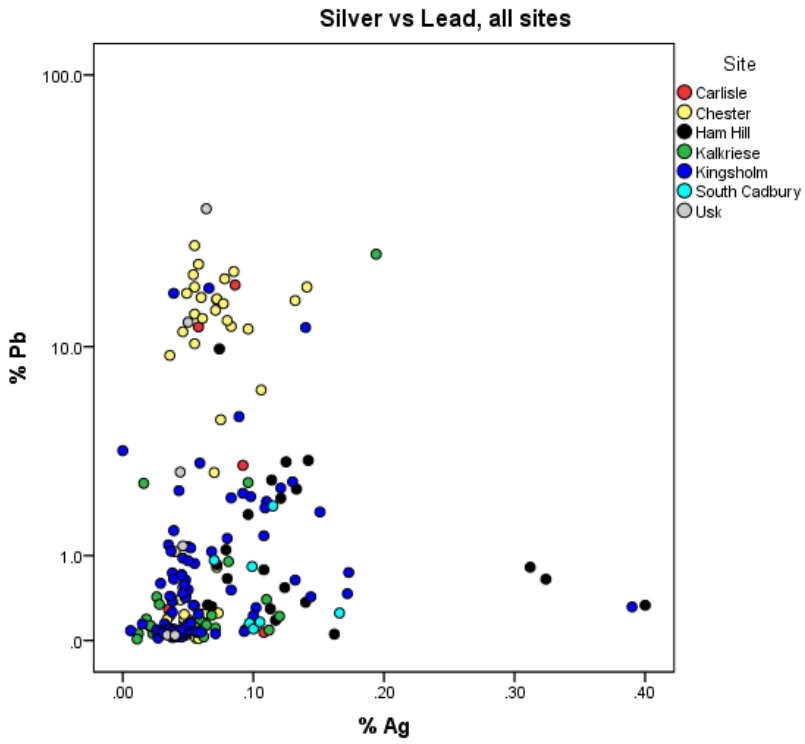

Figure 5.169 Lead v. silver for all sites, showing no correlation between the two elements.

When silver and lead are plotted against each other, no clear correlation is visible (Fig. 5.169). In antiquity, silver could be extracted from lead through the cupellation process. The lead would be oxidised to form litharge (PbO), leaving noble metals such as silver and gold behind. The litharge could then be smelted so that de-silvered lead was obtained by reduction (Kassianidou 2003). Silver and lead would behave similarly when plotted against each other had the lead been involved in silver extraction.

In the case of iron (Fig. 5.170), most of the samples fall in the range between 0.1% and 0.4%, but show a very large dispersion, from levels barely over the limit of detection to almost 1% (Chester and Kingsholm, for instance).

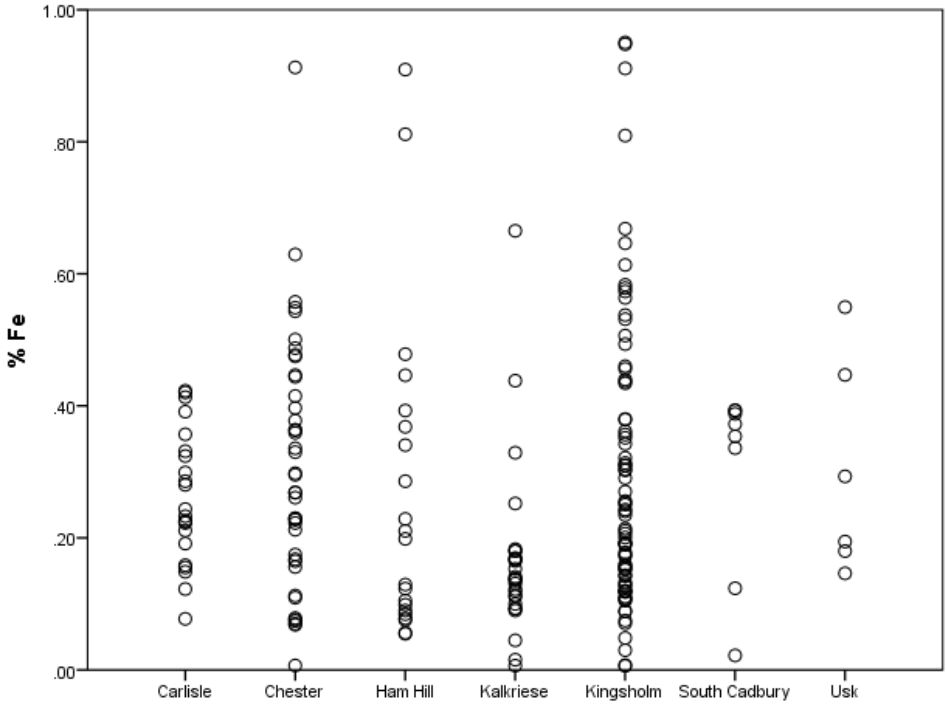

Figure 5.170 Dotplot showing distribution for iron (scaled to the copper) for all sites.

The nickel shows more compact ranges, generally centred on 0.02% (Fig. 5.171). The objects from Kalkriese show a slightly higher amount of nickel than the other sites, except for a group of objects from Kingsholm, with enough members so that they are not considered as outliers. Of the 8 members of this high nickel group, six of them are plates and two are *lorica segmentata* fittings. The group of objects from Kalkriese with lower nickel content can be more clearly seen in a bivariate plot, such as in Figure 5.172, where it is set against antimony.

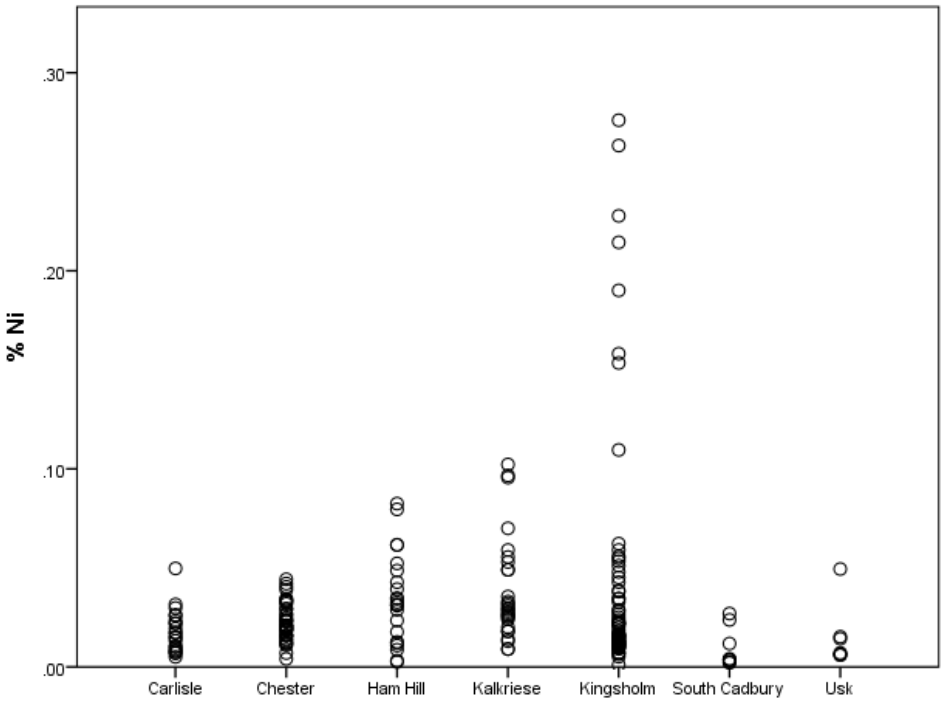

Figure 5.171 Dotplot showing distribution for nickel (scaled to the copper) for all sites.

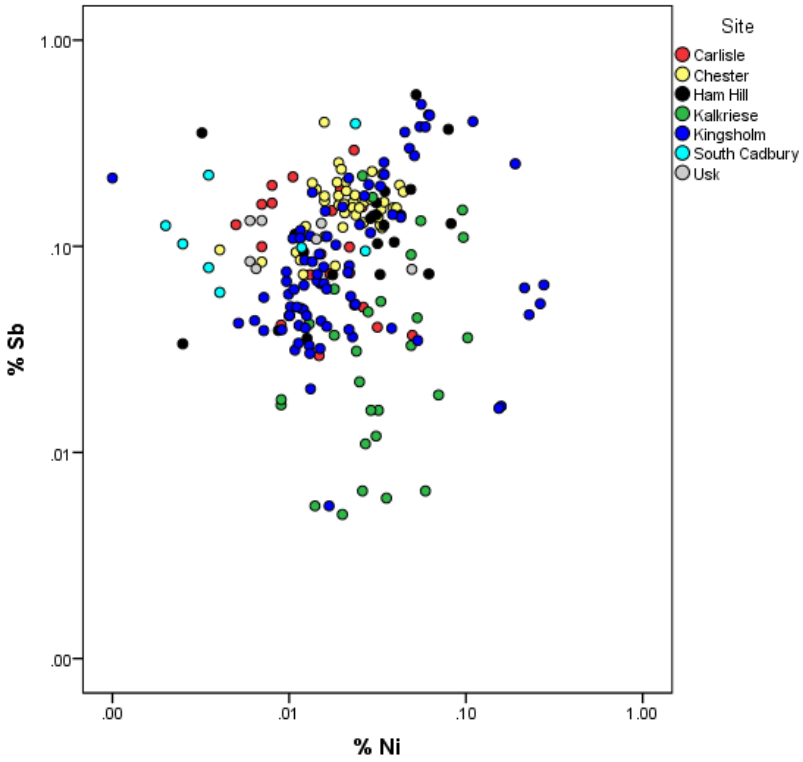

Figure 5.172 Bivariate plot. Nickel v. antimony for all sites (both elements scaled to the copper).

The contents of manganese are the highest for Chester (with typical values of 0.01%), followed by Carlisle, with both sites showing a large dispersion in manganese percent values (Fig.

5.173). The rest of the sites have lower manganese contents, centred on 0.002% (in the order of magnitude of the limit of detection).

Most of the objects have cobalt contents concentrated around 0.01% (Fig. 5.174). However the level of dispersion is high and values five times higher can be seen for several of the sites.

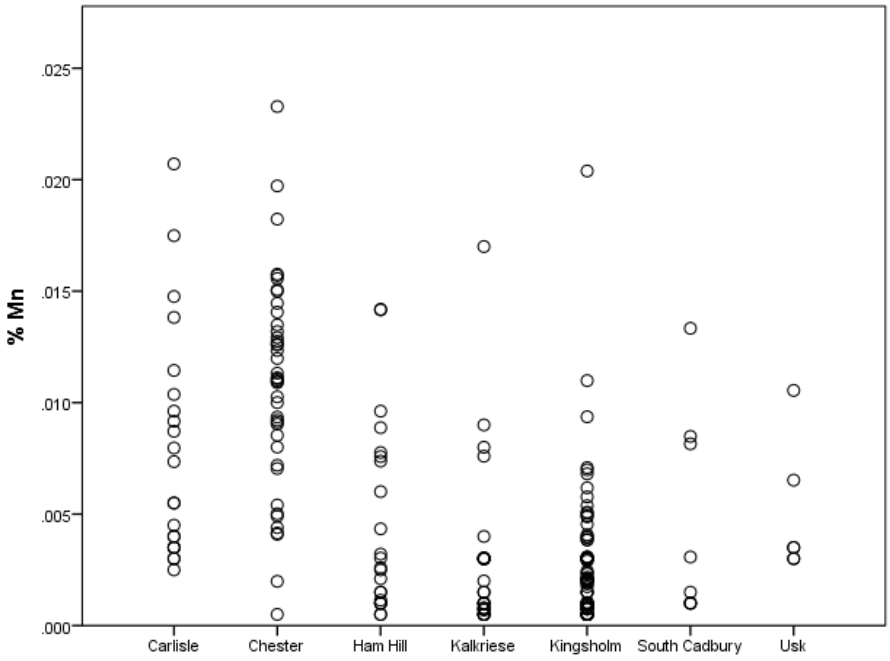

Figure 5.173 Dotplot showing distribution for manganese (scaled to the copper) for all sites.

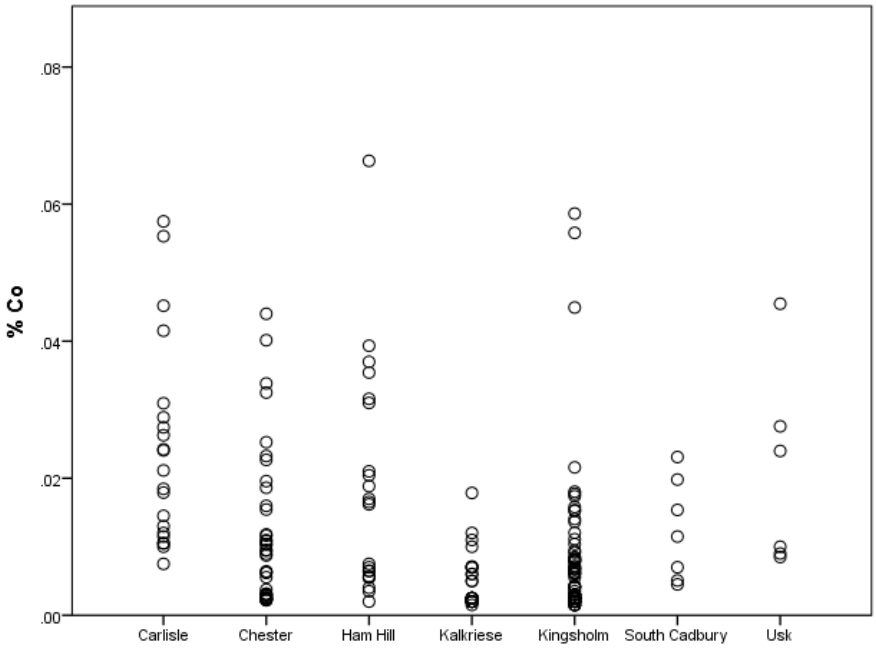

Figure 5.174 Dotplot showing distribution for cobalt (scaled to the copper) for all sites.

Most of the samples have antimony contents ranging from 0.05% to 0.2% (Fig. 5.175). Antimony contents are lower for Kalkriese and some of the objects from Kingsholm, which show a broad dispersion, ranging from lower than the limit of detection to almost 0.5%.

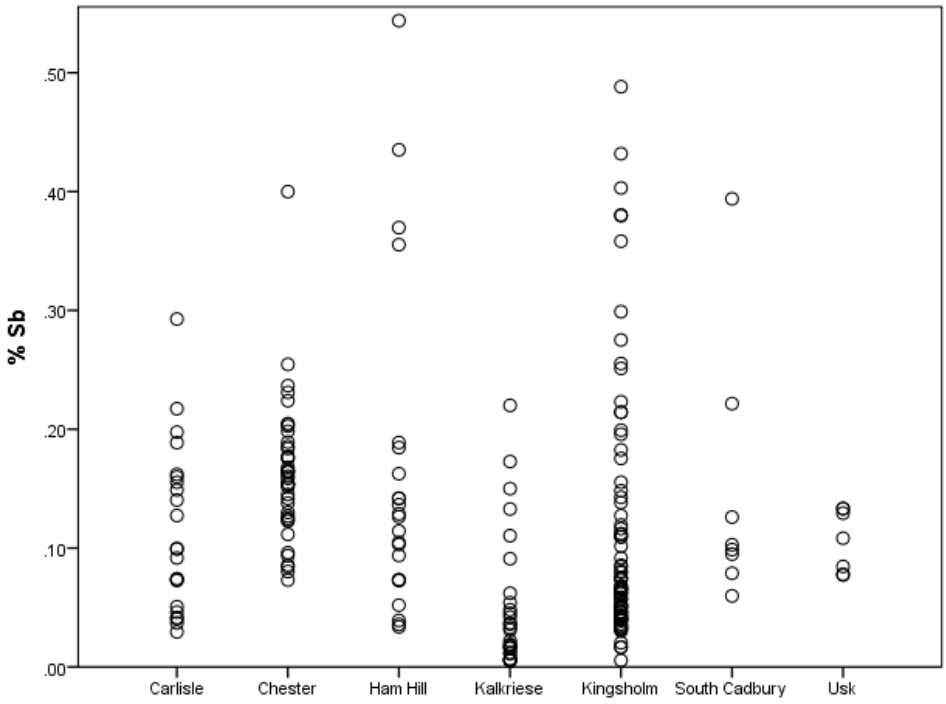

Figure 5.175 Dotplot showing distribution for antimony (scaled to the copper) for all sites.

Antimony is present in relatively higher quantities for bronzes and gunmetals (Fig. 5.176). The majority of the bronzes contain between 0.3% and 0.4% antimony, whilst the median in the case of the brasses is 0.1%. There does not seem to be a correlation between antimony and tin (Fig. 5.177) or when antimony is plotted against lead (Fig. 5.178), an element to which it is related, being able to form solid solutions together. However, most of the objects with higher antimony content in leaded alloys belong to later periods (the objects from Chester dating from periods after the 2nd century).

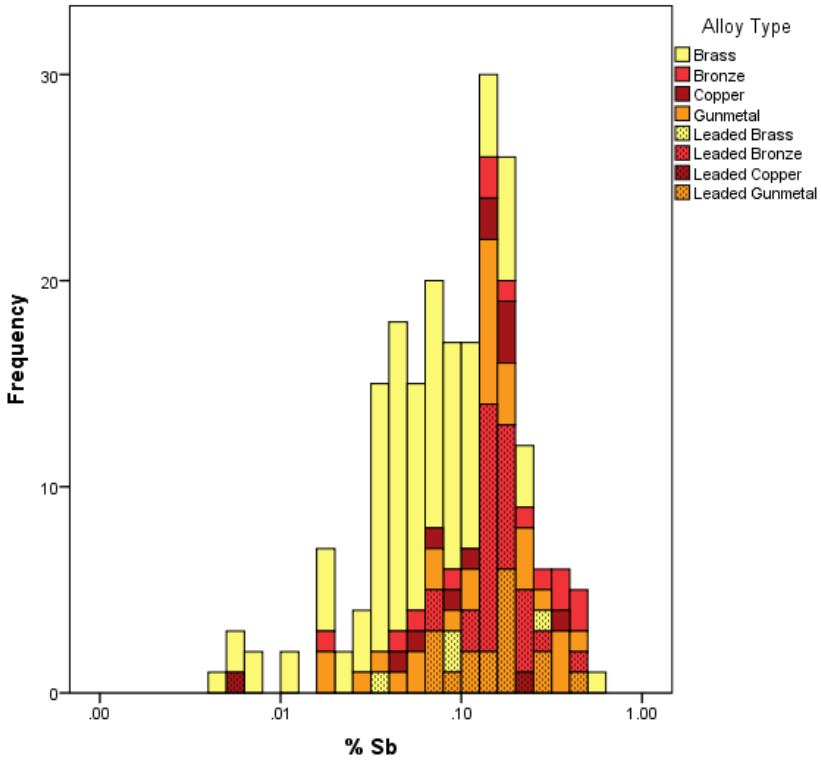

Figure 5.176 Barplot showing distribution for antimony (scaled to the copper) for all sites by alloy type.

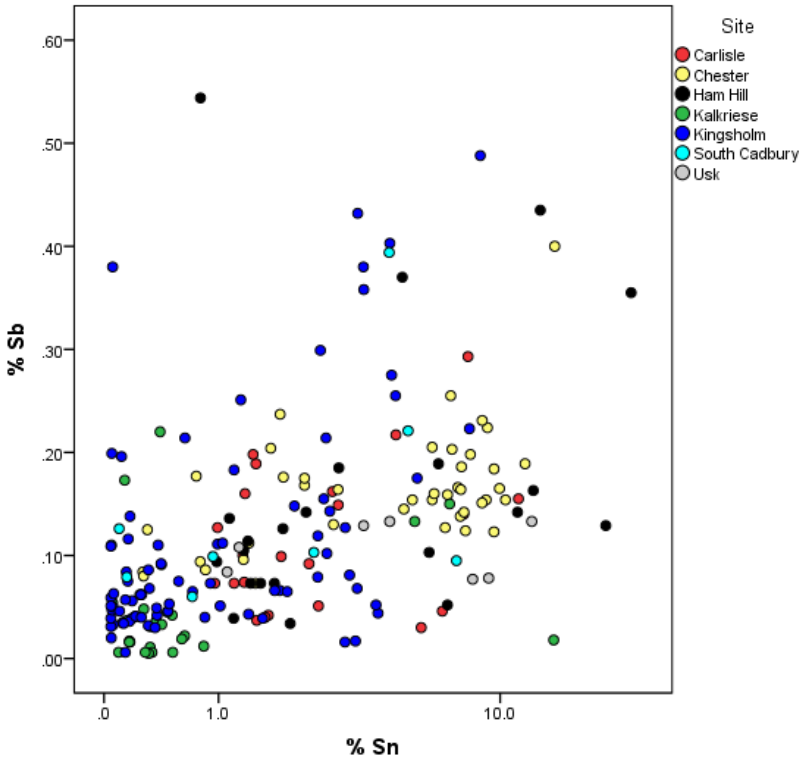

Figure 5.177 Bivariate plot. Tin v. antimony for all sites.

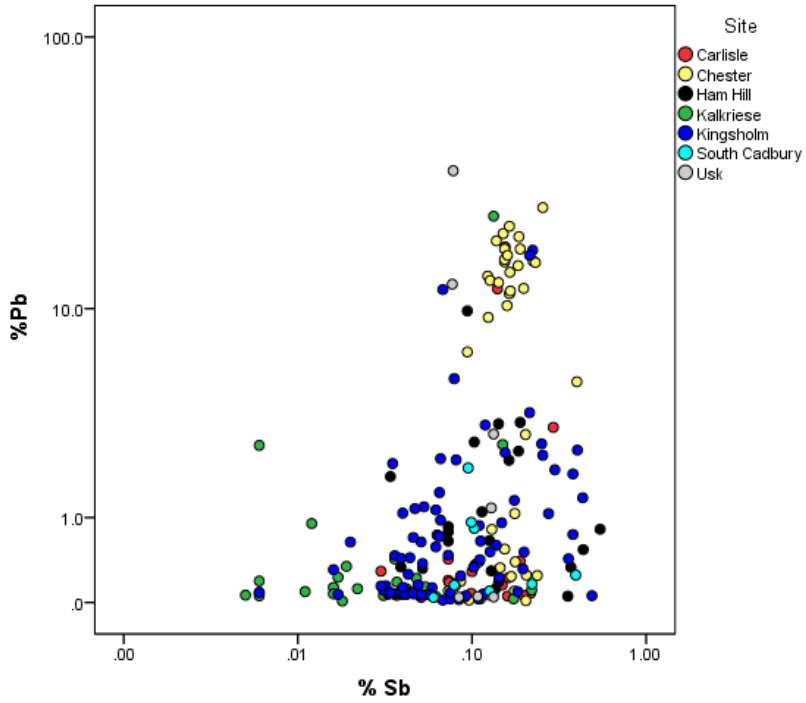

Figure 5.178 Bivariate plot. Antimony v. lead for all sites.

Arsenic contents (Fig. 5.179) are concentrated below 0.1% for most of the objects analysed in this thesis, a value which is situated slightly above or equal to the limit of detection. It can be seen that Ham Hill and South Cadbury have arsenic contents slightly higher than the other sites. However, dispersion, as in the case with antimony is high, and all the sites, except Kalkriese, show samples with arsenic contents as high as 0.5%.

Antimony and arsenic seem to be slightly correlated, as can be seen from Figure 5.180, considering values above the limit of detection of arsenic (roughly above 0.1%). In the same plot, higher quantities of antimony can be seen for bronzes and gunmetals, as noted above.

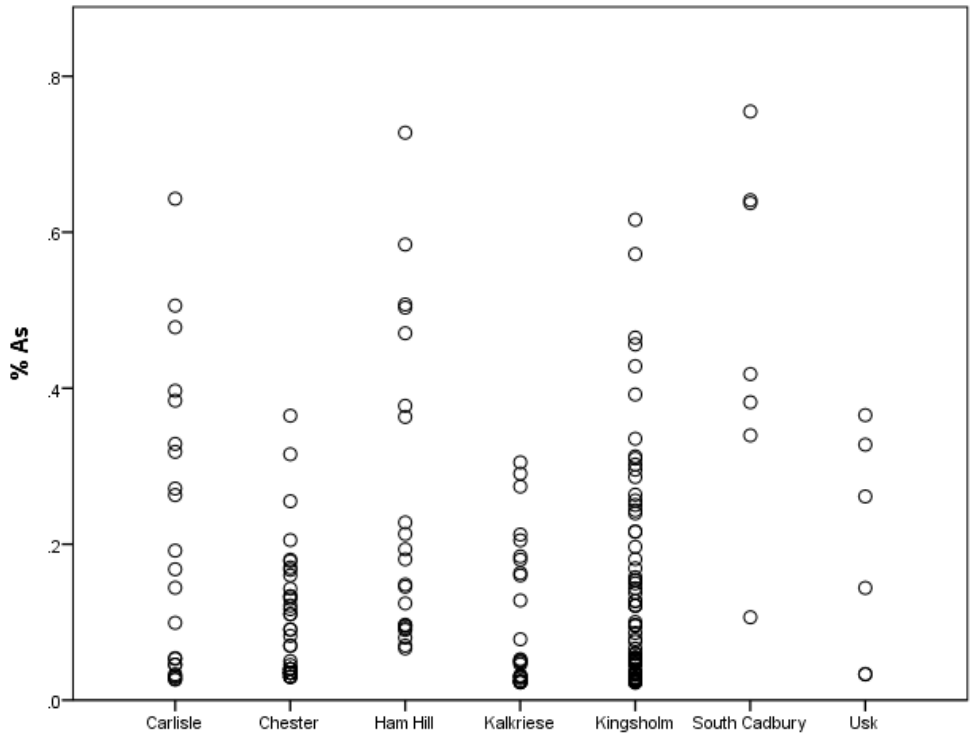

Figure 5.179 Dotplot showing distribution for arsenic (scaled to the copper) for all sites.

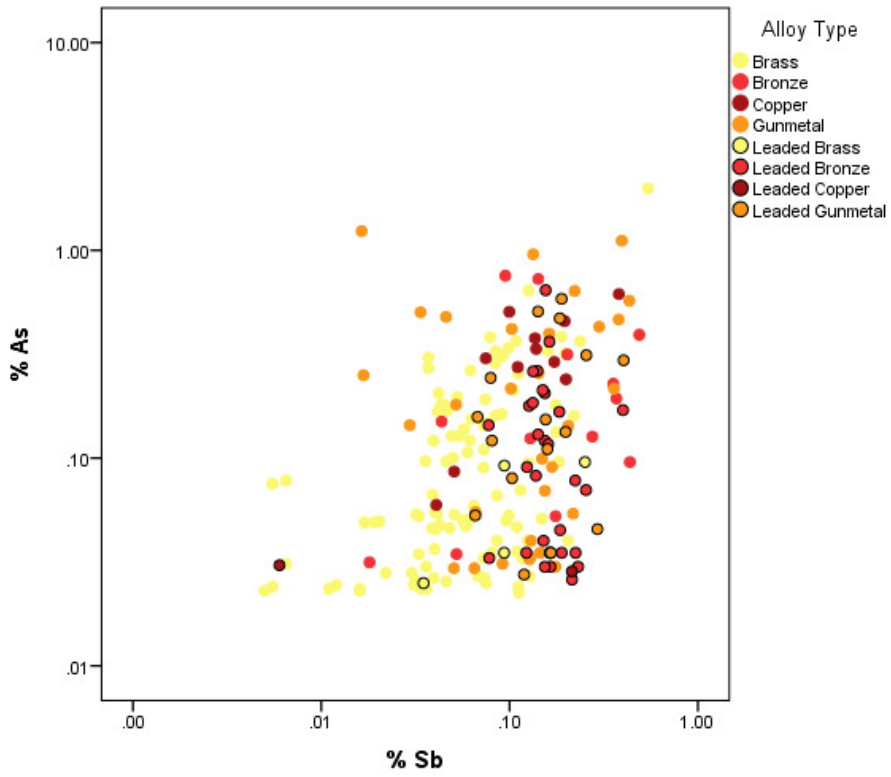

Figure 5.180 Bivariate plot. Antimony v. arsenic for all sites (both elements scaled to the copper), colour coded by alloy type.

5.10.3 Trace elements by legion.

This section shows the results of the analyses when unit type classifications are used with the aim of comparing different military units by their trace element composition. Traditional military group attributions (see Chapter 4) were employed to represent all the analysed samples in bivariate plots: *Legio II Augusta* included Ham Hill and South Cadbury Castle, *Legio XX Valeria Victrix* was associated with Usk, Kingsholm, Chester and Carlisle and *legiones XVII-XIX* were grouped together as Kalkriese military units. From the bivariate plots above (see Chester), alloy type and some trace elements like antimony are distinctive in later time periods. Only samples from before mid 2nd century were used in the bivariate plots of this section in order that all the samples were comparable with each other. Additionally, only nickel, silver, cobalt and nickel were used, to account for lower precision levels that arsenic might have.

A nickel v. cobalt plot (Fig. 5.181) does not show a clear separation between *legio II* and *legio XX*. The Kalkriese legions, whilst falling within the compositional range of cobalt that legions *II* and *XX* exhibit, can be seen as showing relatively low levels of cobalt when compared with the other two military units. Nickel tends to be slightly higher for the Kalkriese group of legions.

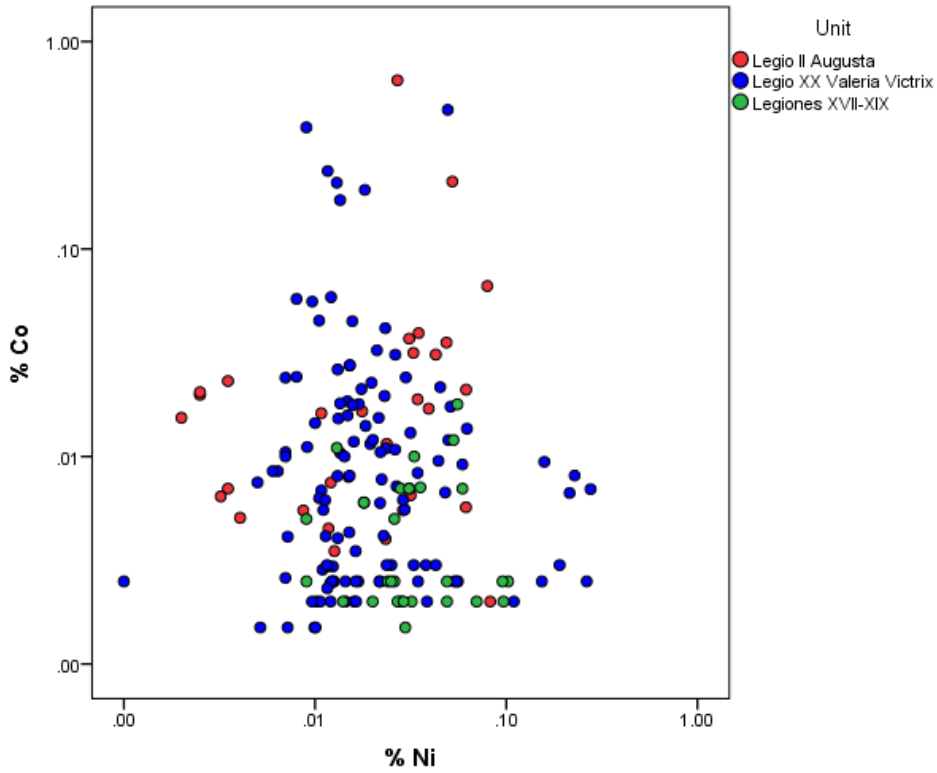

Figure 5.181 Bivariate plot. Nickel v. cobalt for all sites, colour coded by military unit (both elements scaled to the copper).

There is not a clear separation between legions *II* and *XX* when nickel and antimony are considered (Fig. 5.182). The same plot shows separation for some of the samples from Kalkriese defined by lower levels of antimony. Similarly to the nickel-cobalt plot (Fig. 5.180), the amount of nickel tends to be higher for the same group.

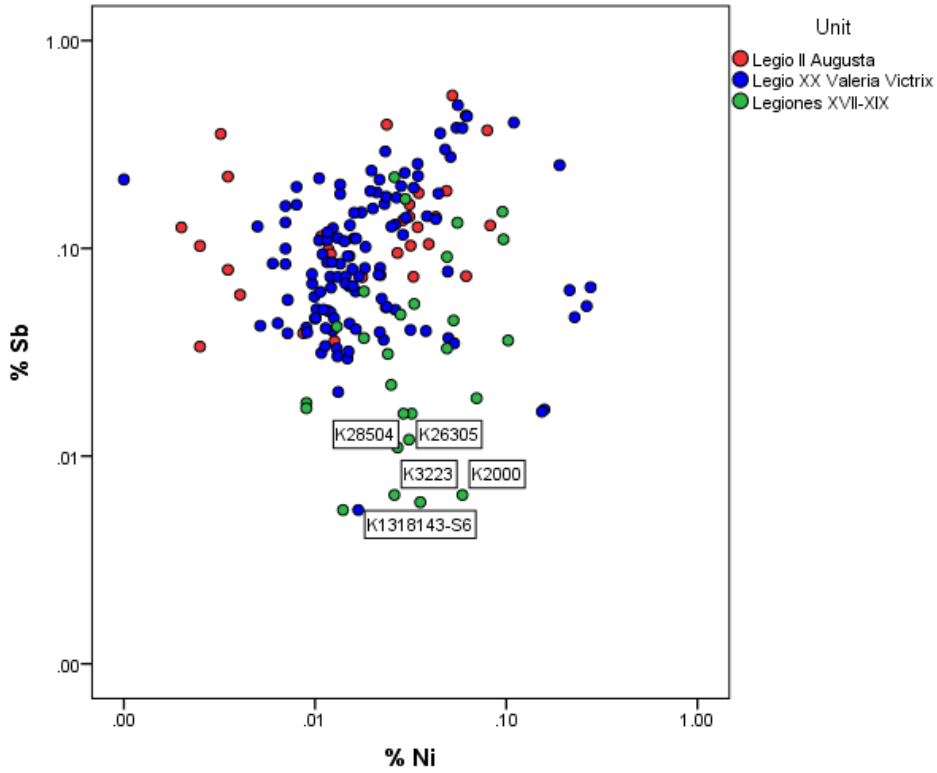

Figure 5.182 Bivariate plot. Nickel v. antimony for all sites, colour coded by military unit (both elements scaled to the copper).

The content of silver tends to be higher for *legio II* (Fig. 5.183), but is similar in both content and dispersion in the case of legions XX, and *XVII-XIX*, the latter group having most of the lowest values.

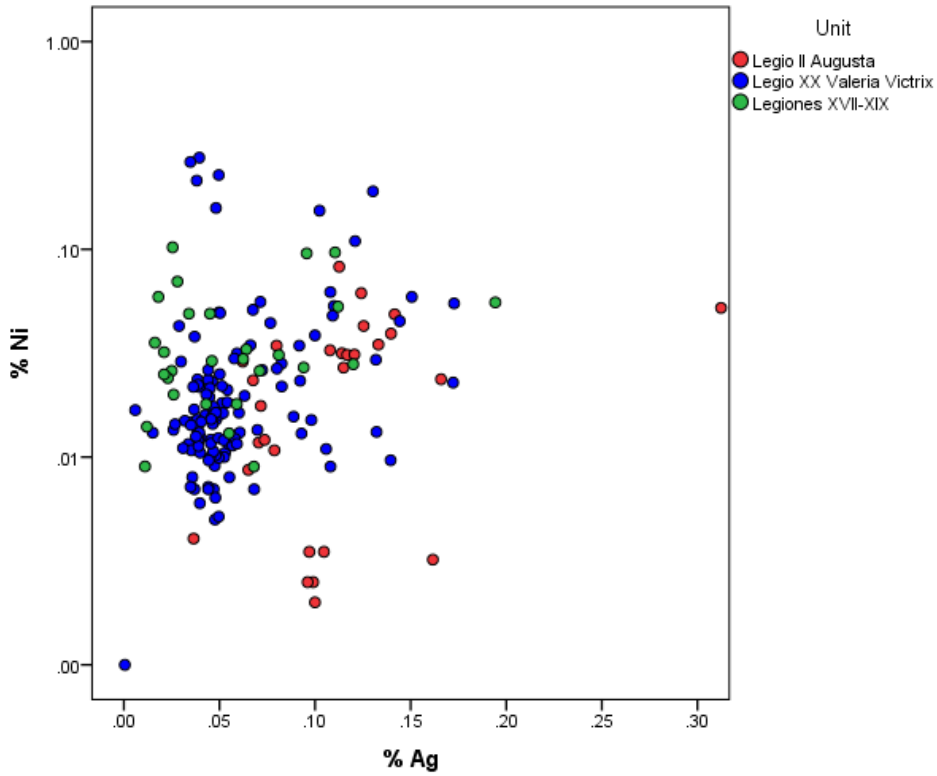

Figure 5.183 Bivariate plot. Silver v. nickel for all sites, colour coded by military unit (both elements scaled to the copper)

The three plots above (Figs. 5.173-5) suggest that the objects from Kalkriese slightly separate from the rest due to levels of nickel and antimony, mainly, and to less extent due to cobalt and silver. However, separation between legions *II* and *XX* is not clear, except for a higher silver content. The following plots of the section (Figs. 5.176-8) show the samples of only legions *II* and *XX* in order to identify trace compositional differences between them.

In the case of nickel and cobalt, there does not seem to be significant differences in either the compositional ranges or the dispersion of the values between legions *II* and *XX* (Fig. 5.184). There is a small group, with objects from *legio II*, with low nickel values, and another group (mainly objects from Kingsholm) with higher nickel content. A similar situation can be noted when comparing antimony and nickel, where both elements overlap (Fig. 5.185).

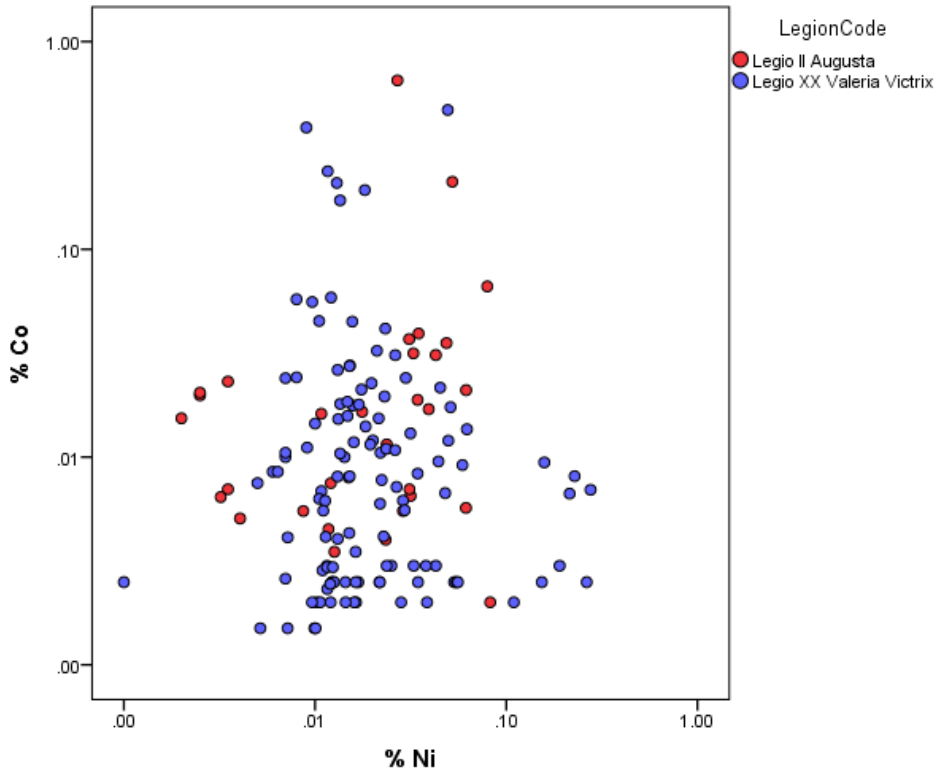

Figure 5.184 Bivariate plot. Nickel v. cobalt for the sites associated with legions *II* and *XX* (both elements scaled to the copper).

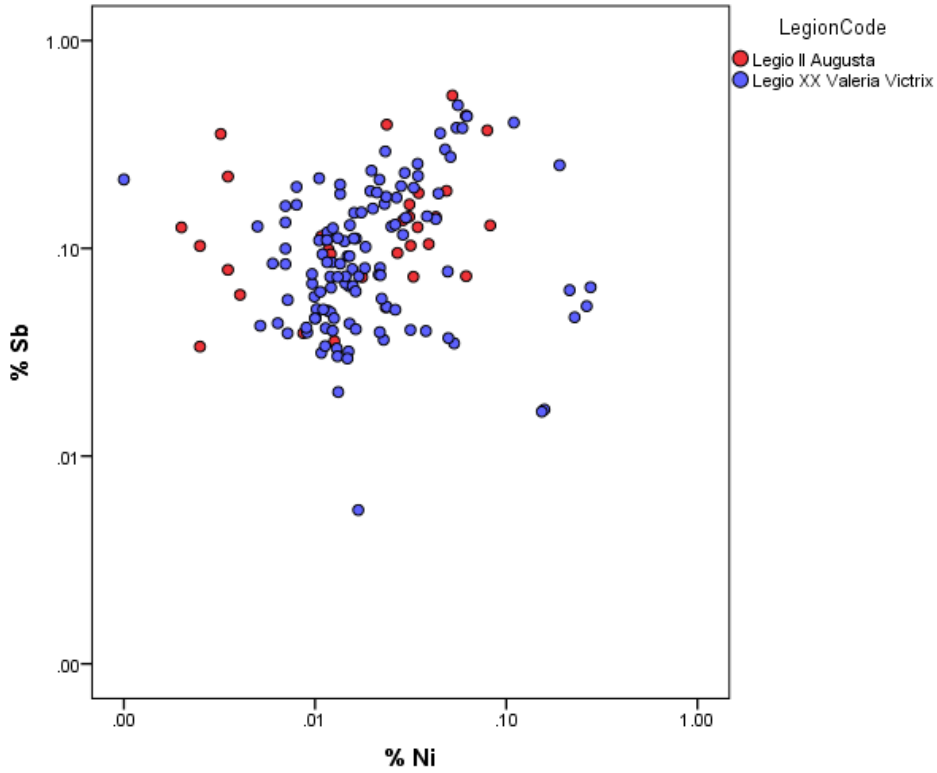

Figure 5.185 Bivariate plot. Nickel v. antimony for the sites associated with legions *II* and *XX* (both elements scaled to the copper).

When silver is examined between the two legions as in Fig. 5.186, where it is plotted against nickel, a relative separation between the two military units can be seen. Most of the samples from *legio XX* tend to be concentrated in a group with low silver content. However, silver dispersion is high and the upper end of the silver content range of *legio XX* shows an overlap with most of the objects from *II Augusta*. Almost all the samples from *legio XX* in this overlap correspond to equipment from Kingsholm.

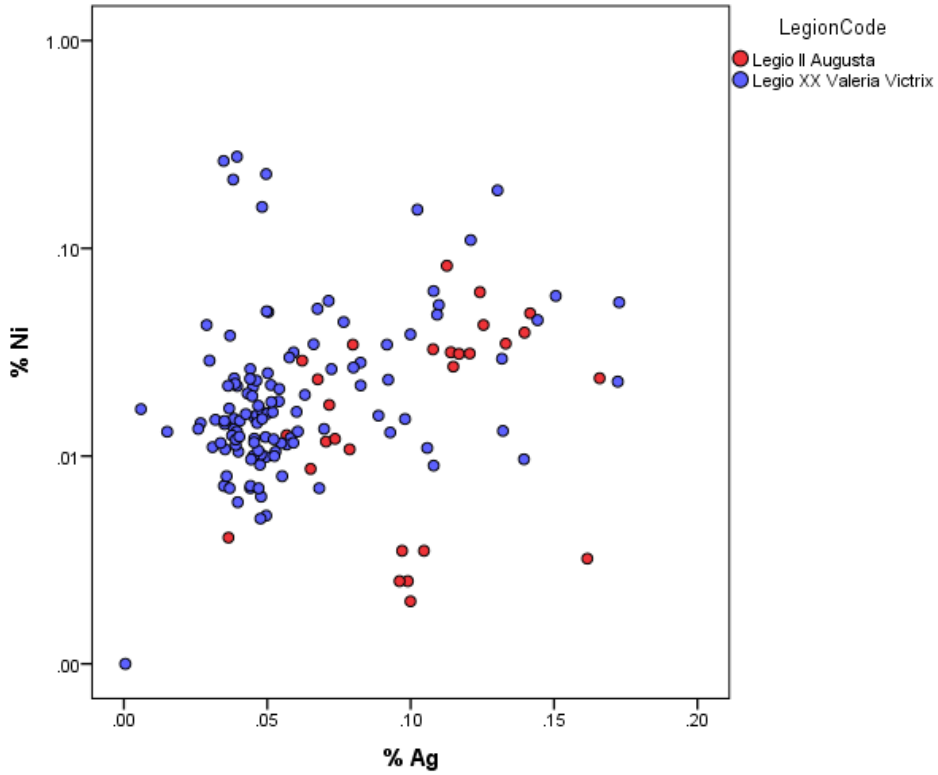

Figure 5.186 Bivariate plot. Silver v. nickel for the sites associated with legions *II* and *XX* (both elements scaled to the copper).

5.11 Metallography of all sites

Grain Size

Dispersion in grain size is variable between sites (Fig. 5.187), it is large for the objects from Carlisle and Kalkriese, but considerably smaller for those objects from Kingsholm. The smallest granular structures were found in the objects from Chester and Kingsholm. The clearest difference is between the material from Kalkriese and Kingsholm, since in each case the objects come from tighter time frames when compared to Chester and Carlisle, the other two sites analysed in this thesis with a considerable number of granular structures identified.

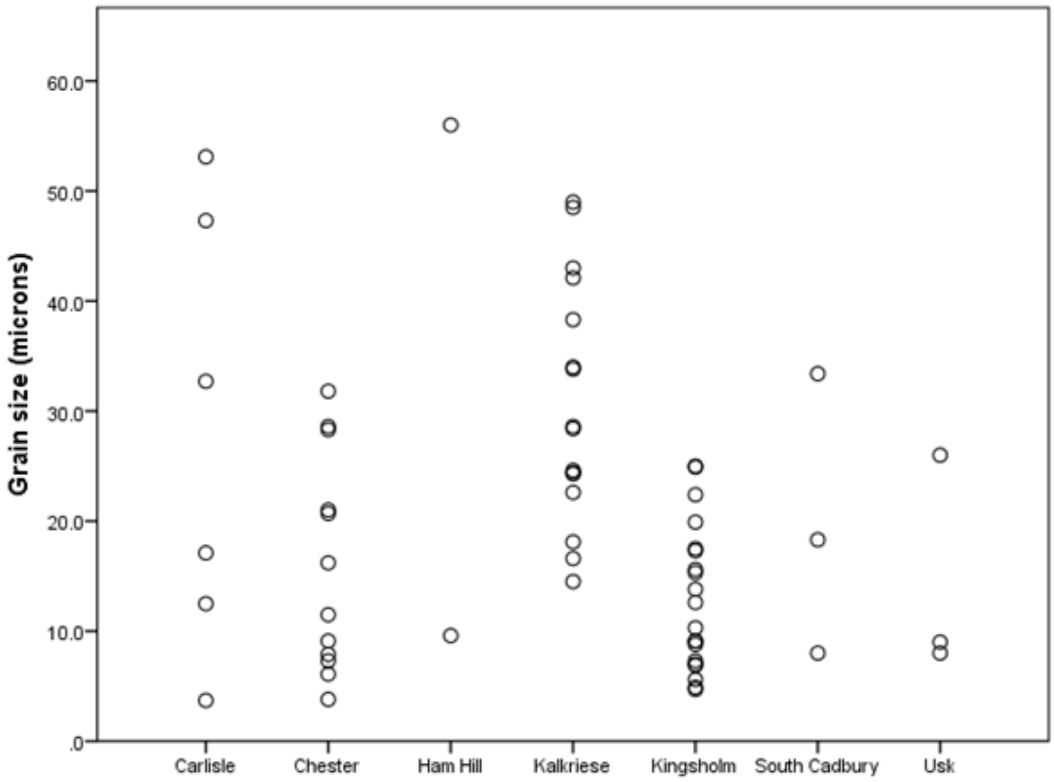

Figure 5.187 Dotplot comparing grain size for sampled objects from all sites in this thesis.

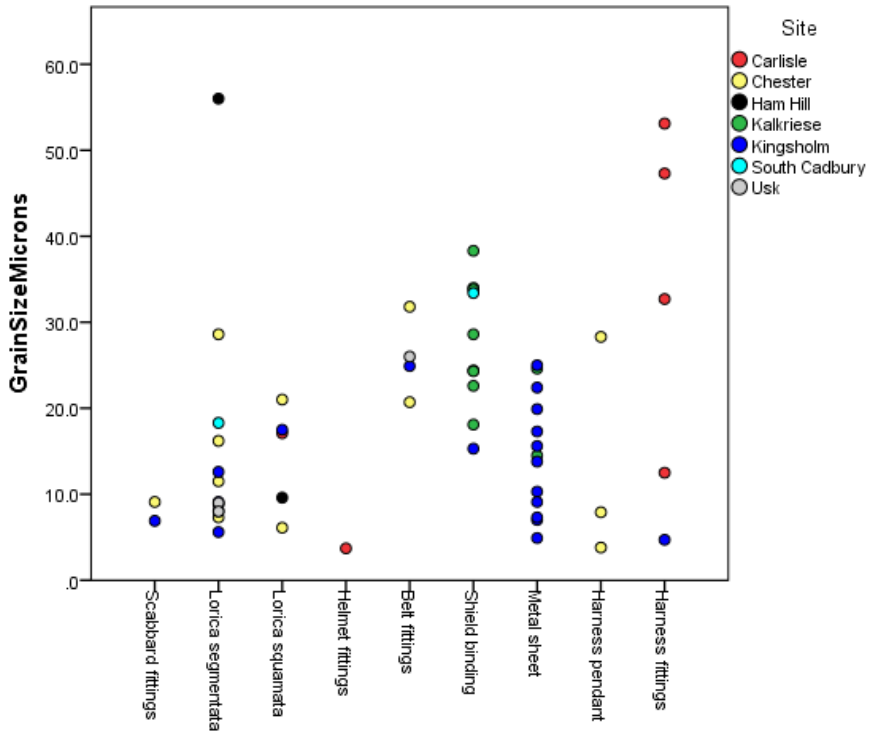

Figure 5.188 Dotplot comparing grain size by object type, colour coded by site.

Grain size was also compared across the different type of objects from which metallographic samples had been taken (Fig. 5.188). Object types with a granular structure are mostly *lorica segmentata* fittings, shield binding fragments, and metal sheet and plate fragments. It can be clearly seen that shield bindings show larger grain sizes for most samples, and larger grain size dispersion, when compared to *lorica segmentata fittings*.

5.12 Multivariate analysis

5.12.1 Principal component analysis (PCA)

Principal component analysis (see Section 3.7.4.4) was performed with IBM-SPSS Statistics Version 20 software using 5 trace elements measured by atomic absorption spectrometry. These 5 elements (silver (Ag), nickel (Ni), cobalt (Co), arsenic (As), and antimony (Sb)) are adequate for metallurgical characterisation (see Section 3.2.2) and are related to the copper. Only objects from the first two centuries AD were considered to ensure comparability between the sites. After considering all alloys together in the analysis, two further analyses were conducted treating brasses only and then bronzes and un-alloyed copper. Prior to analysis the data were logarithmically transformed to account for non-normality in the distribution of the data (see Section 3.7.4.3).

Before running the analysis, exploratory tests were run to evaluate if the data were suitable for principal component analysis. The software provides two tests for detecting structure in the data: the Kaiser-Meyer-Olkin measure of sampling adequacy (Kaiser 1970; Kaiser & Rice 1974), and Bartlett's test of sphericity (Bartlett 1937).

The first test run was the Kaiser-Meyer-Olkin, which measures the variance in the variables attributed to correlation; a measure with a value greater than 0.5 is considered acceptable for considering PCA analysis (Hair *et al* 2009). For these data, a value of 0.535 was obtained (Table 5.4), which is interpreted as the data not having a strongly defined structured, but still adequate for PCA.

Bartlett's test of sphericity evaluates whether the correlation matrix is an identity matrix (where all the elements in the diagonal are 1 and the rest are 0, meaning there is no correlation), which would render PCA inappropriate. The test is based on the null-hypothesis that the variables of the correlation matrix obtained from the variables of the data are not correlated. A significance value of less than 0.05 would indicate the probability of the correlation matrix being an identity, and therefore the hypothesis of the absence of a correlation would be rejected (Hair *et al* 1998). For the

data of this thesis it can be seen from Table 5.4 that the significance value is .000, which indicates that correlation exists within the data variables (chemical elements).

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.535
Bartlett's Test of Sphericity	Approx. Chi-Square	68.989
	Df	6
	Sig.	.000

Table 5.4 SPSS generated table for PCA. Tests showing adequacy for PCA.

PCA analysis initially extracted four components, three of which account for 88% of the variance seen in the data. The first component explains 41% of the data, whilst the second and third are responsible for 27% and 19%, respectively (Table 5.5). The remaining component explains only a small amount of the data (each explains less variance than a single variable) and was left out of the analysis.

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	1.662	41.539	41.539	1.662	41.539	41.539
2	1.073	26.825	68.363	1.073	26.825	68.363
3	.767	19.187	87.550	.767	19.187	87.550
4	.498	12.450	100.000			

Table 5.5 PCA of the dataset showing cumulative variance explained by the three extracted components.

The specific elements bearing a larger weight on each component can be identified through the magnitude of the coefficients (loadings) of the component matrix (Table 5.6). Silver and antimony are the main elements defining Component 1 (all with very similar weights), whilst nickel has the highest importance in Component 2. Cobalt and antimony show the largest coefficients for Component 3.

	Component		
	1	2	3
Ag	.839	.132	-.004
Ni	.378	.830	.303
Co	.534	-.585	.582
Sb	.728	-.154	-.580

Table 5.6 SPSS generated table of the component matrix for the three extracted components, showing loadings for each one.

A score can be obtained for each case (or sample) using the component matrix coefficients seen in Table 5.6. In this way the three variables can be visualised in bivariate scatter-plots: for Component 1 against Components 2, 1 v. 3, and 2 v. 3.

When the two most important Components, 1 and 2 (they explain 62% of the data) are plotted against each other (Fig. 5.189) and colour coded by site, it can be seen that some of the objects from Kalkriese form a separate group towards the left-hand side of the graph. The objects from the other sites (including the remaining samples from Kalkriese) overlap in the graph, and only the objects from South Cadbury are oriented towards the bottom right corner of the graph.

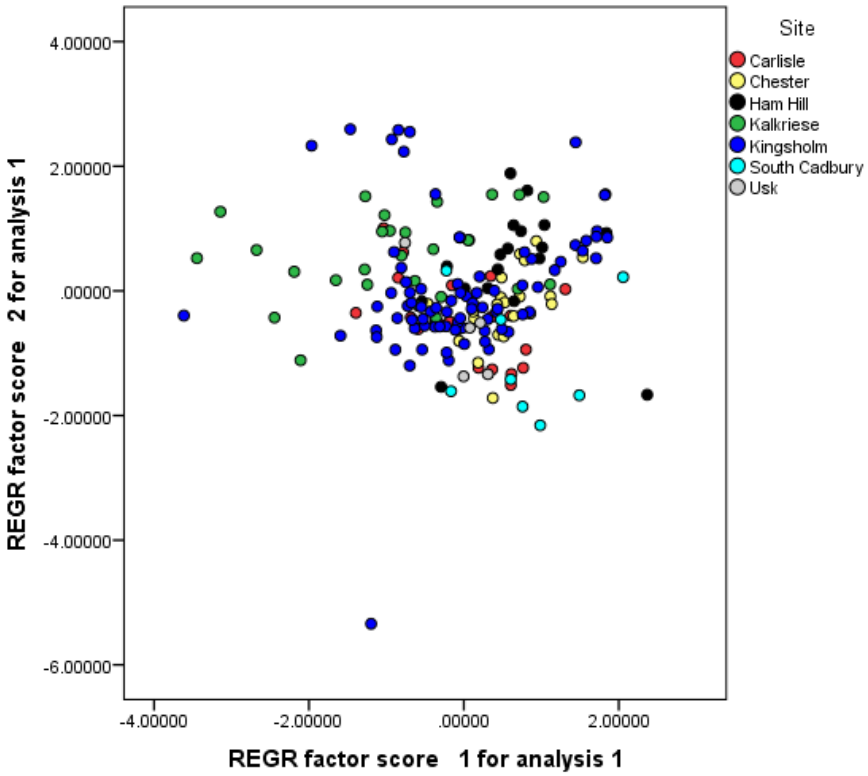

Figure 5.189 PCA. Bivariate plot of Component 1 v. Component 2 colour coded by site.

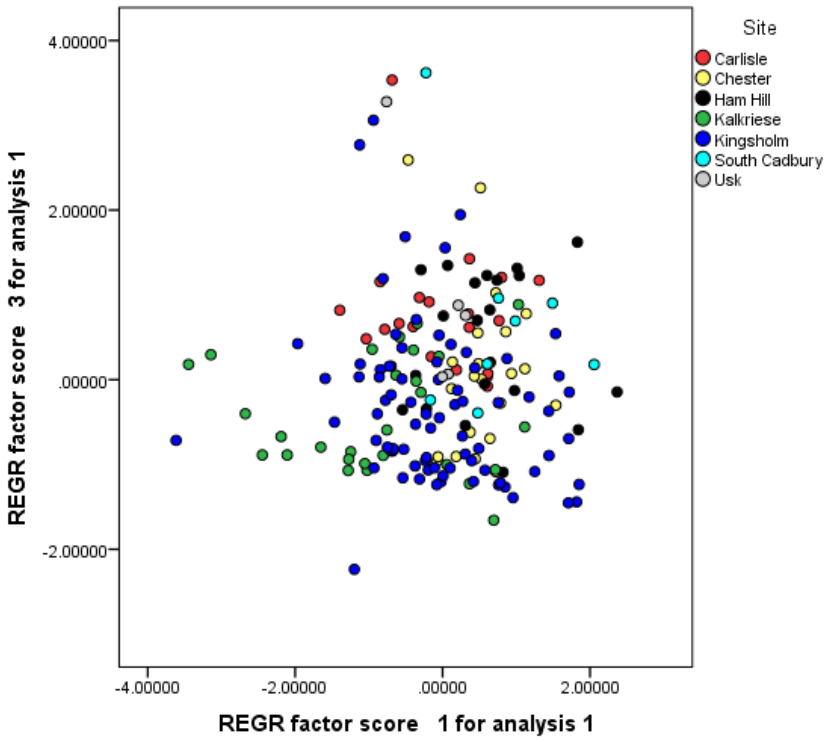

Figure 5.190 PCA. Bivariate plot of Component 1 v. Component 3 colour coded by site.

The plot showing components 1 and 3 (Fig. 5.190) also show the sites overlap, and the partial separation of the objects from Kalkriese. This is not so readily observed in the remaining plot, Component 2 v. 3 (Fig. 5.191), where there is no clear separation between sites.

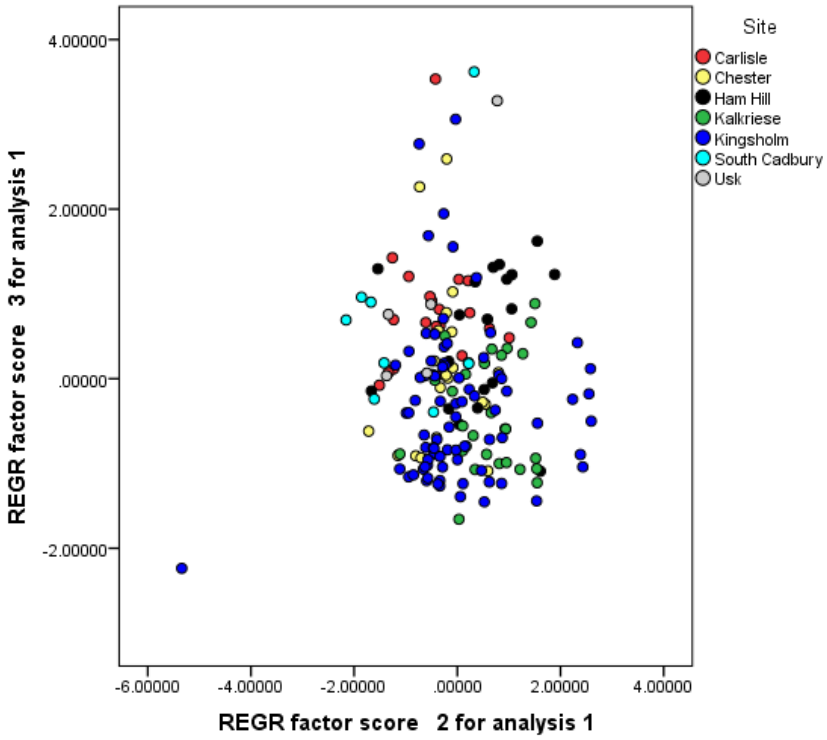

Figure 5.191 PCA. Bivariate plot of Component 2 v. Component 3 colour coded by site.

The separate group for plots Components 1 v. 2 and 1 v. 3 is formed by the same objects, a situation which places component 1 as more influent in the separation than the other groups, followed by Component 2. From the component matrix coefficients, and considering the dominant influence of Components 1 and 2, it can be seen that silver, nickel and antimony are the most important elements contributing to the separation. However, as can be seen for the plots and as indicated by the Kaiser-Meyer-Olkin measure, PCA does not point to a clear correlation between the four variables that could define separate groups.

PCA of brass objects

The analysis was run again but considering brasses only. The three Components obtained explained 86% of the variability. In Figure 5.192 it can be seen that a very small group of brasses (four objects) from Kalkriese is singled out by Component 2, along the vertical axis. Figure 5.193 shows that there is no separation between groups caused by Component 3 (vertical axis).

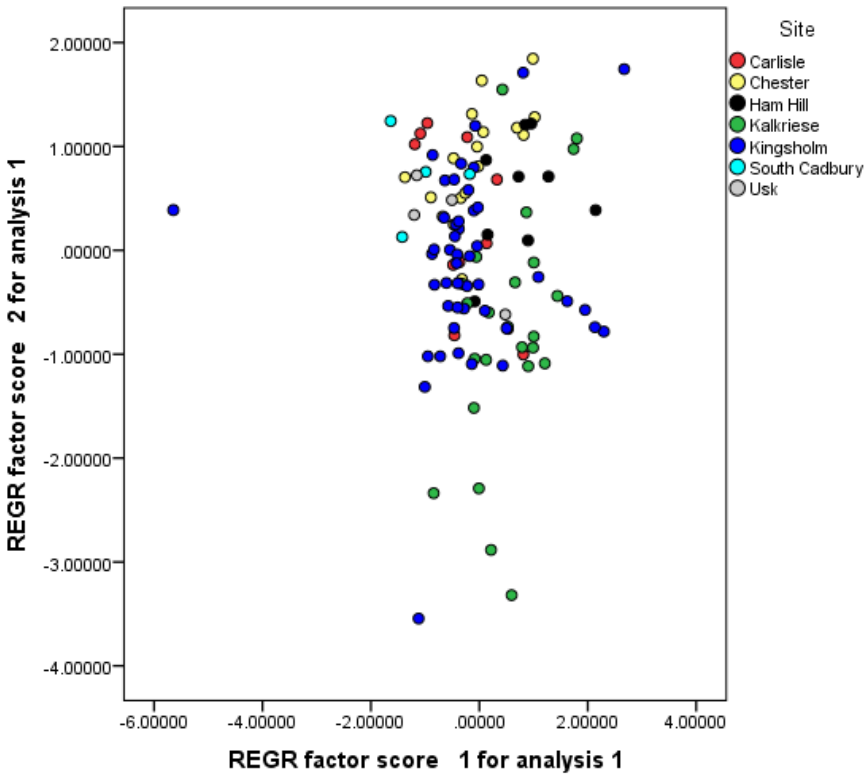

Figure 5.192 PCA (brasses) Bivariate plot of Component 1 v. Component 2 colour coded by site.

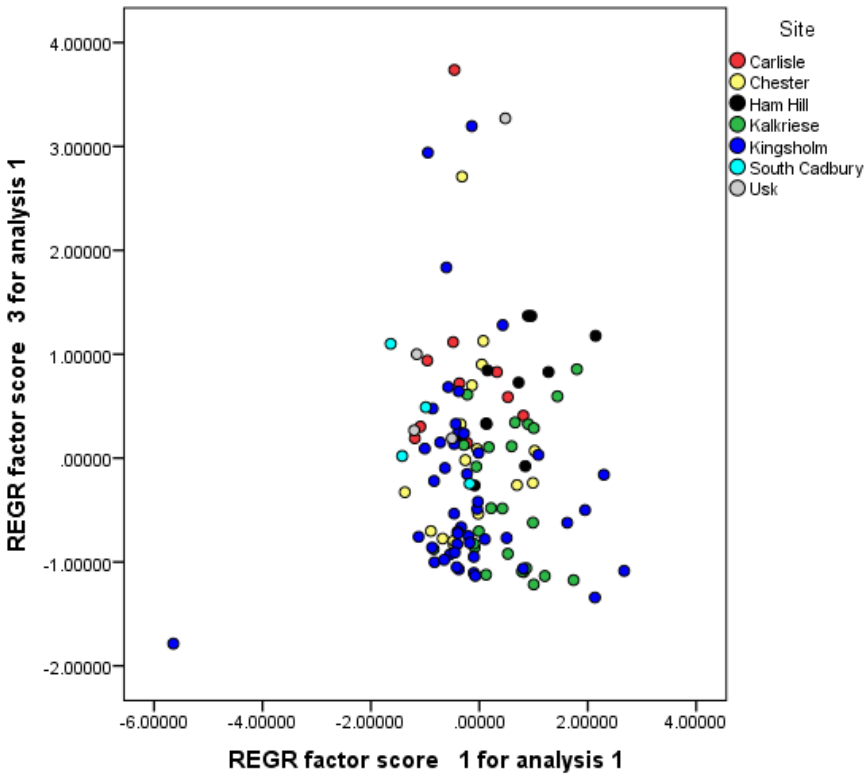

Figure 5.193 PCA (brasses) Bivariate plot of Component 1 v. Component 3 colour coded by site.

	Component		
	1	2	3
Ag	.460	.239	.181
Ni	.772	-.157	-.163
Co	-.108	-.185	.964
Sb	-.078	.938	-.180

Table 5.7 SPSS generated table of the component matrix for the three extracted components (for brass objects), showing loadings for each one.

The separation between the brass objects of Kalkriese from the other sites is not very clear, but it is mainly due to antimony and nickel, which are the main elements explaining the variance of the data: Component 2 is dominated by antimony, and nickel is the most influential element in Component 1 (Table 5.7).

PCA of bronze and un-alloyed copper objects.

Even if the sample size is considerably smaller by considering only bronzes and un-alloyed copper objects for principal component analysis, it was still possible to obtain a PC analysis, as Kaiser-Meyer-Olkin measure was 0.53 and Bartlett's test of sphericity is still valid at a significance of 0.000 (less than the threshold 0f 0.05). The three components obtained accounted for 92% of the behaviour of the data. The most influential elements by component were silver and nickel for Component 1, and cobalt and nickel for Component 2 (Table 5.8).

	Component		
	1	2	3
Ag	.893	-.004	-.144
Ni	.796	-.283	-.400
Co	.222	.960	-.140
As	.613	.026	.780

Table 5.8 SPSS generated table of the component matrix for the three extracted components (for bronze and un-alloyed copper objects), showing loadings for each one.

When the scores are calculated for each sample and the components plotted against each other, no visible groups can be seen (Fig. 5.194), and the four samples surrounding the main bulk of objects can be considered as outliers. Objects from Kingsholm and Kalkriese show a higher spread along Components 1 and 2, which explain 71% when taken together.

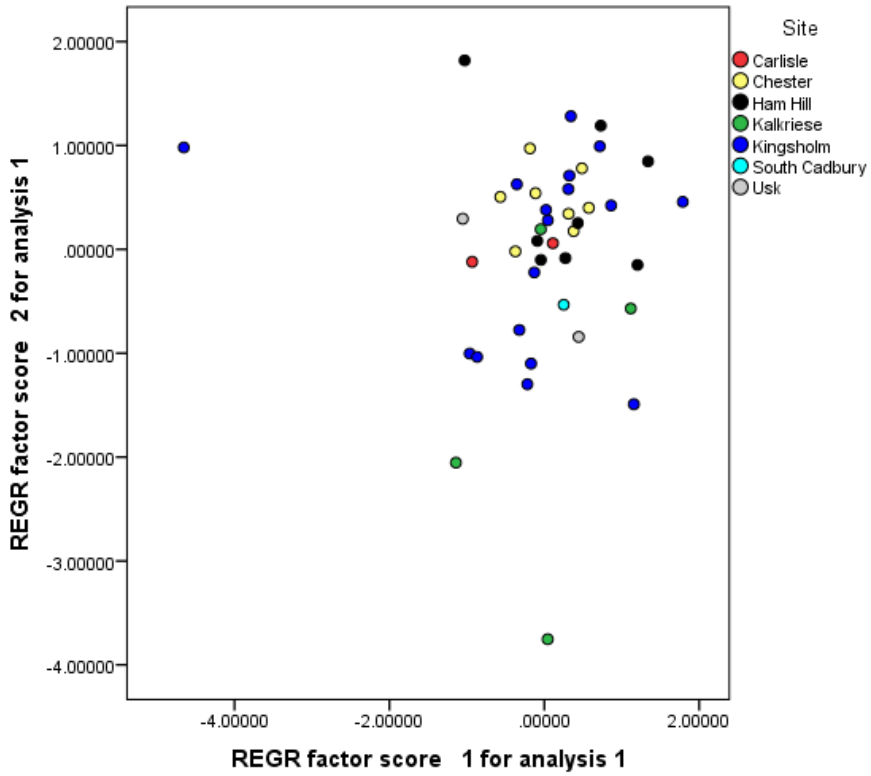

Figure 5.194 PCA (bronze and un-alloyed copper objects) Bivariate plot of Component 1 v. Component 2 colour coded by site.

5.12.2 Linear discriminant analysis (LDA)

The same elements selected for principal component analysis were used for discriminant analysis: silver, nickel, cobalt and antimony. Only samples from the first two centuries AD were considered so that they were comparable with each other. Since this method requires an *a priori* attribution of the cases (samples) to a single group, the different sites were associated with a legionary group on the basis of archaeological criteria (see Chapter 4): Ham Hill and South Cadbury were associated with *legio II Augusta*; Usk, Kingsholm, Chester, and Carlisle with *legio XX Valeria Victrix;* and Kalkriese with legions XVII, XVIII and XIX. For the purposes of discriminant analysis in this thesis, *legio II Augusta* was identified as Group I, *legio XX Valeria Victrix*, as Group 2, and the troops at Kalkriese as Group 3.

The analysis was run first with all alloy types considered, and then three additional analyses considering brass objects only, then considering bronzes and copper-objects, and finally gunmetals, to identify any possible differences between alloy type in group formation.

Since the number of groups is three, the number of functions to describe the variance of the data is the number of groups minus 1, or 2 (Stamatis 2002: 136). Since eigenvalues explain the

proportion of the variance explained by the function, it can be seen from Table 5.9 that Function 1 is the strongest function, explaining 74% of the variance.

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	.507[a]	73.6	73.6	.580
2	.181[a]	26.4	100.0	.392

Table 5.9 Eigenvalues for Functions 1 and 2 and cumulative % of variance explained.

Wilk's lambda is a measure of the strength of the function to discriminate into groups, as it is expresses the variance in the discriminant scores not explained by differences amongst the groups. A lower value indicates that the function has a higher discriminative power, which is the case of function 1 (see Table 5.10). For example, in the case of function 1, a lambda of 0.542 means that 54.2% of the variance is not explained by function 1. The two discriminant functions produced by the analysis are linear combinations of five variables whose coefficients are associated with the five chemical elements chosen (Table 5.11).

Test of Function(s)	Wilks' Lambda	Chi-square	df	Sig.
1 through 2	.562	101.522	10	.000
2	.846	29.346	4	.000

Table 5.10 Wilk's lambda, a measure of significance for each function.

	Function	
	1	2
Ag	.376	.765
Ni	-.571	-.080
Co	.275	-.163
Sb	.560	-.866
As	.238	.541

Table 5.11 Coefficients for each of the Discriminant functions, and their associated elements.

Once the coefficients for each function are obtained, an individual score can be calculated for each case (sample). In this case a set of scores for each function can be plotted against each other and colour coded based on the group attribution set before the analysis. Three additional scores, centroid scores, are calculated then, and are also based on the group attribution prior to the analysis. A centroid score for a group is calculated using variable (chemical element) means, rather than each case (sample) in the discriminant function. Centroids represent the most typical value for the group. As can be seen in Figure 5.195, group centroids (marked with a square) are clearly separated for the three groups. The distance between centroid 3 and 1 is the longest, followed by that between 3 and 2. Still, centroids 1 and 2 are clearly separated. When all the individual scores for both functions are considered, separation is still clear between Groups 1 and 3. The degree of separation between the scores from Groups 1 and 2, and between Groups 2 and 3 is not as high, but is still noticeable.

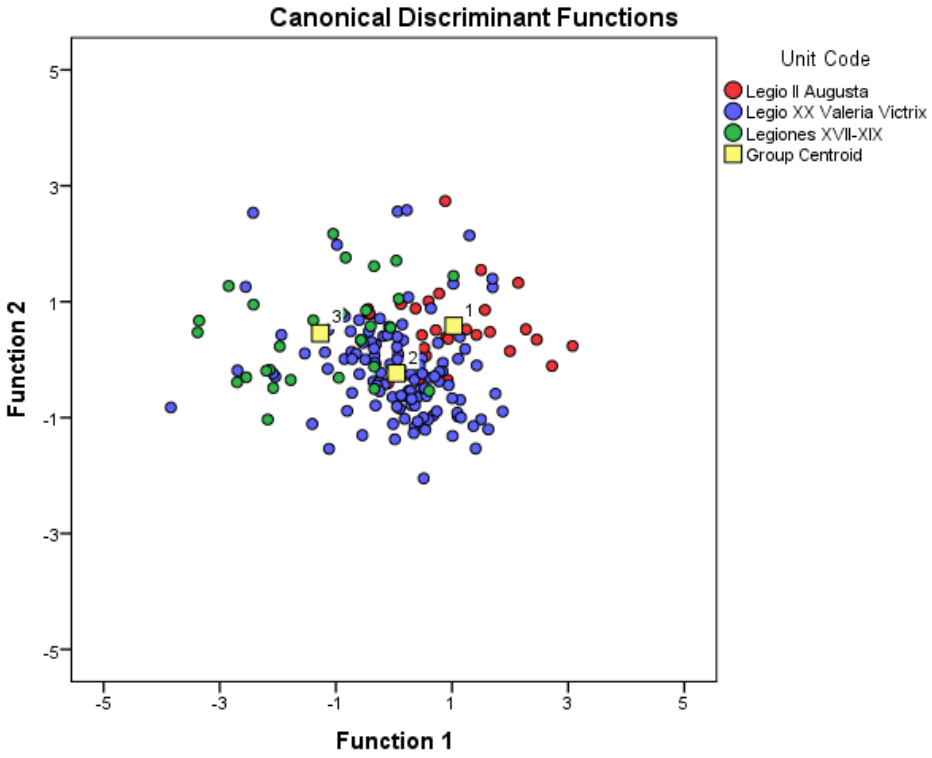

Figure 5.195 Conformance to three groups: Legion II (1), Legion XX (2), and German Legions (3).

Discriminant analysis also predicts group membership and compares this prediction with the initial group attribution (Table 5.12). The table shows rows with pre-analysis attribution and column with predicted groups. The analysis attributed *legio II* membership to 76% of the objects originally classified as such. Prediction percentages were 68% and 75% for legions XX and the group of *XVII-*

XIX, respectively. Cumulatively, the analysis was able to classify 70% of the cases according to their original attribution.

		Legion	Predicted Group Membership			Total
			Legio II	*Legio XX*	L XVII-XIX	
Original	Count	*Legio II*	22	4	3	29
		Legio XX	17	85	24	126
		L XVII-XIX	3	4	21	28
	%	*Legio II*	75.9	13.8	10.3	100.0
		Legio XX	13.5	67.5	19.0	100.0
		L XVII-XIX	10.7	14.3	75.0	100.0

Table 5.12 DA predicted group membership compared to *a priori* classification.

DA of brass objects

When considering brasses only, two discriminant functions were obtained with which components scores were calculated for each sample. These scores and the group centroids can be seen in Figure 5.196, where a separation between groups can be seen. This separation is mainly expressed by Function 1, where nickel and antimony oppose each other (Table 5.13). The distance between the centroids along the vertical axis (Function 2) is smaller, and is related to silver and antimony. 74% of the cases were classified in accordance with pre-analysis attribution, which is a very similar prediction to that obtained where all alloy types were considered together.

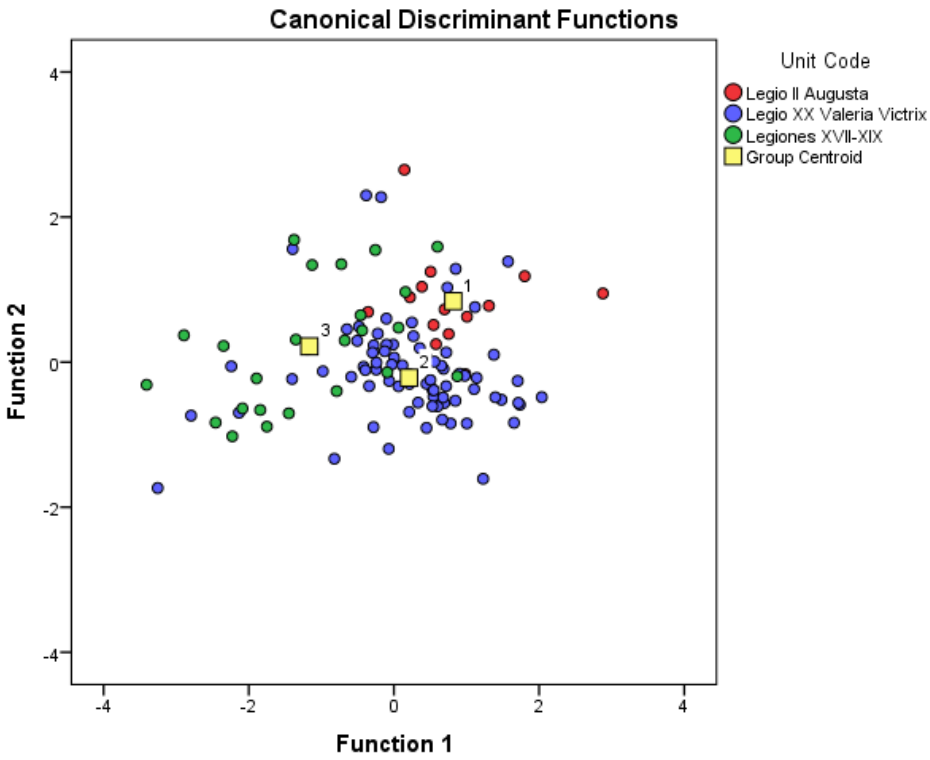

Figure 5.196 Conformance to three groups (considering brasses only): Legion II (1), Legion XX (2), and German Legions (3).

	Function	
	1	2
Ag	.252	1.067
Ni	-.701	-.115
Co	.321	-.056
Sb	.657	.620

Table 5.13 Coefficients for each of the discriminant functions (brass objects), and their associated elements.

DA of bronze and un-alloyed copper objects

In the case of the bronzes and the un-alloyed copper objects the two functions obtained behave in a similar way to the analysis that considered just the brasses, with antimony and nickel opposing in Function 1, and silver and antimony dominating in Function 2 (Table 5.14).

	Function	
	1	2
Ag	.606	1.024
Ni	-.573	-.199
Co	.464	.069
Sb	.732	-.715

Table 5.14 Coefficients for each of the Discriminant functions (bronze and un-alloyed copper objects), and their associated elements.

When the obtained centroids and scores for Function 1 and 2 are plotted against each other (Fig. 5.197) there is again a separation between centroids, with Group 3 (the military units from Kalkriese) being the most distinctive. Groups 1 (*legio II*) and 2 (*legio XX*) are closer in the direction of the Function 1 axis, and slightly differ to one another mainly due to Function 2 (where silver and arsenic dominate).It seems, as in the case of the brasses, that levels of nickel and antimony differentiate Group 3 from the others in the case of bronze and un-alloyed copper objects. Conversely, silver separates Groups 1 and 2, but this separation is very small.

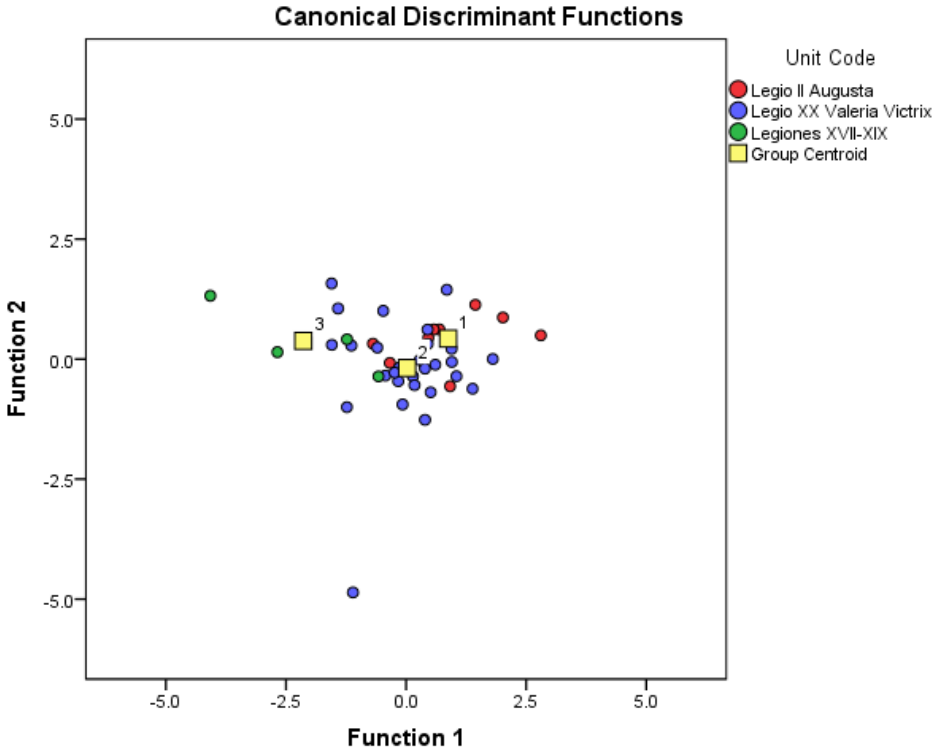

Figure 5.197 Conformance to three groups (considering bronze and un-alloyed copper objects): Legion II (1), Legion XX (2), and German Legions (3).

DA of gunmetal objects

Since there are only two groups for *a priori* attribution (no gunmetal objects from Kalkriese, which provides the third group for the previous analysis, were sampled), only one discriminant function was obtained when just gunmetal objects were considered (Table 5.15).

	Function
	1
Ag	.865
Ni	-.534
Co	.216
Sb	-.346
As	.381

Table 5.15 Coefficients for the gunmetal Discriminant function, and its associated elements.

The distribution of scores for the discriminant function can be seen as a histogram (Fig. 5.198), where a clear separation between groups (right vertical axis) can be seen. The elements responsible for the separation seem to be silver and arsenic. There is a caveat to this analysis, however: it has to be considered that the sample size for the group with the pre-analysis attribution of Group 1 is small, considering the number of variables (one for each element: 5).

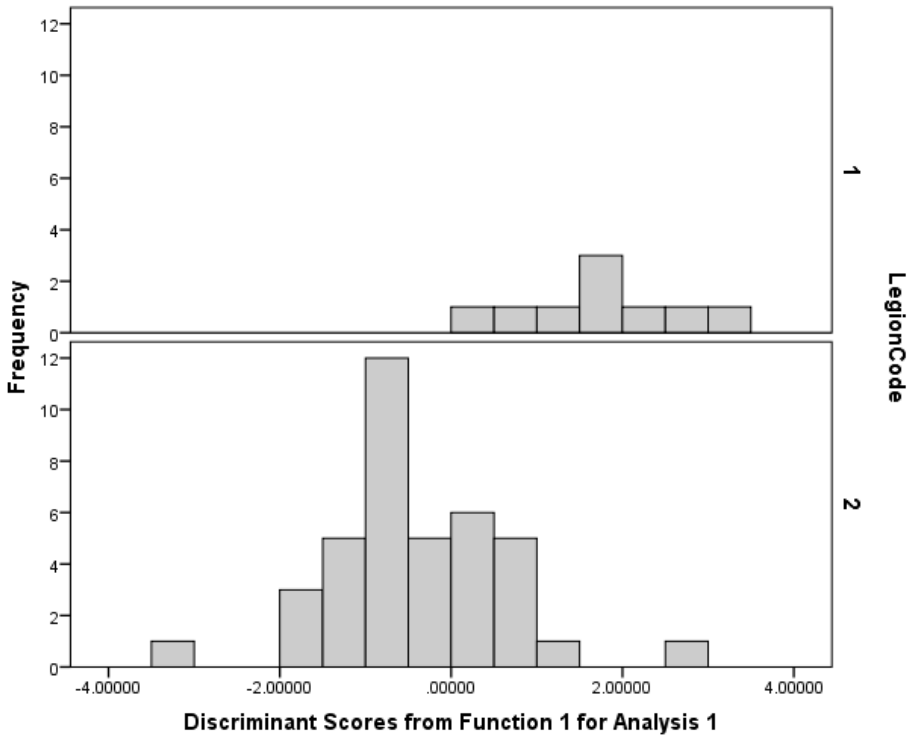

Figure 5.198 Conformance to two groups (considering gunmetal objects only): Legion II (1), Legion XX (2).

DA of *legio II* and *legio XX*.

As it was noted in Section 5.10.3, a separation between legions *II* and *XX* was not clear considering different bivariate plots. Discriminant analysis then was used to explore if inter-elemental correlations could indicate a clear separation between the two military units. The coefficients for the function obtained can be seen in Table 5.16, where silver is clearly the most dominant element explaining variance between both military units.

Element	Function
	1
Ag	1.017
Ni	-.462
Co	.177
Sb	.042

Table 5.16 Discriminant analysis coefficients for the obtained function considering legions *II* and *XX.*

Scores were obtained for each sample on the basis of the coefficients in Table 5.16 and were plotted as histograms to look for a visual separation (Fig. 5.199). The two groups are not clearly separated, as there is an important overlap between discriminant scores for those legions. However, the means of the discriminant scores are different, due to the dominance of silver in the discriminant function.

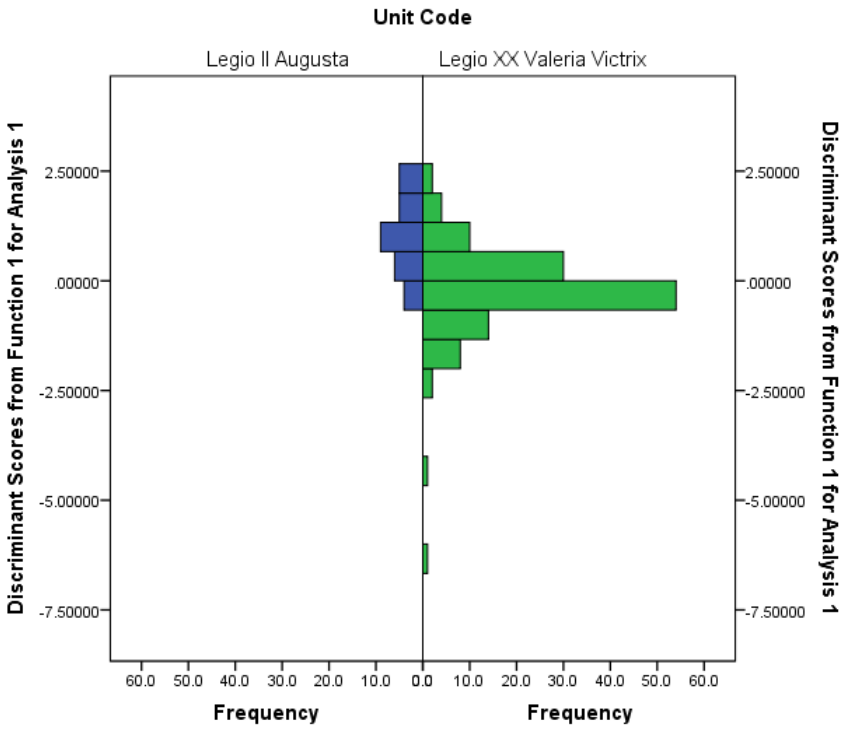

Figure 5.199 Discriminant scores distribution for the function obtained, by military unit.

To test for separation of the group conformed by legions *XVII-XIX* relative to legions *II* and *XX*, the scores obtained when all units were considered together were plotted as histograms (Fig. 5.200). It is clear that the distribution of the objects associated with legions *XVII-XIX*, is different to that of legions *II* and *XX* combined, even if there is an overlap.

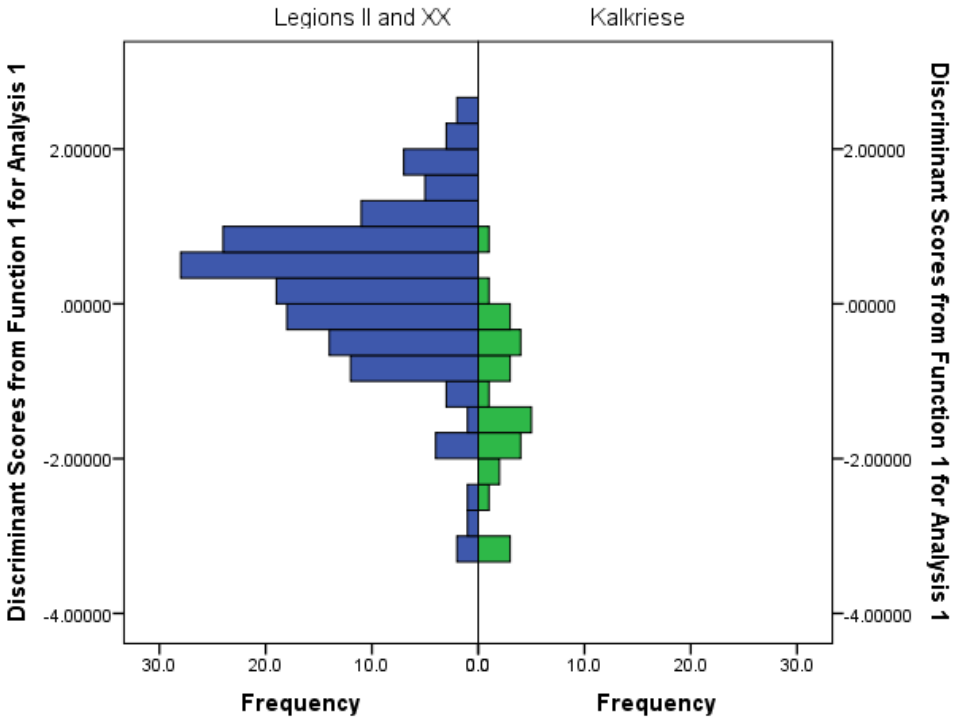

Figure 5.200 Discriminant scores distribution for the function obtained, by military unit.

The coefficients obtained by DA (Table 5.17) show that the elements antimony and nickel have the highest absolute values. These are the main elements contributing to this separation, working in opposite directions along the vertical axis on Figure 5.200.

Element	Function
	1
Ag	.044
Ni	-.527
Co	.351
Sb	.806

Table 5.17 Discriminant analysis coefficients for the obtained function considering legions *II* and *XX* together and the group formed by legion *XVII-XIX*

5.13 Summary of results

The last section of this chapter is a summary of the results and some specific features that were found in the assemblage after analysis. Each site is considered first, and then all the sites together are taken in account, ending with multivariate analysis.

Cadbury Castle:

- 50% of the objects analysed are brasses

Ham Hill

- Brass accounts for 40% of the objects
- Brasses have a lower level of arsenic when compared to the other alloys
- There is a correlation between antimony and cobalt, and between silver and nickel
- Tinned brass scales: tinning shows η and ε phases. The scales were heat treated at 250°C.
- Gilded roundel: plating was added by leaf-gilding, as mercury was not found in the gold.

Carlisle

- There is a higher proportion of brass objects (50%), followed by gunmetals.
- There is a possible separate group formed by horse harness fittings (arsenic vs. antimony plot), which has higher contents of arsenic and antimony.
- Signs of a correlation of non-horse harness gunmetals in Ni-Co plot were found.

Usk

- A *lorica segmentata* hinged buckle could have been silvered.

Chester

- There is a higher proportion of leaded bronzes (but mostly from later periods), followed by brasses. If only the first two centuries are considered however, 50% of the objects are brasses.
- A lower nickel content for brass objects, when compared to bronzes, was found. This is a function of time: the amount of nickel is higher in later objects (after the 2nd century AD).
- There is a higher silver content in the leaded bronzes: this is also related to time period.
- There is a pewter-plated *lorica segmentata* tie.

- Tinning was found on a brass scale.
- *Lorica segmentata* and *squamata* fittings have similar grain sizes.

Kingsholm

- 57% of the objects in the assemblage are made of brass.
- A tin-zinc inverse correlation was found, which is remarkable, as the objects are contemporary. This inverse correlation is well known when long periods of time are considered (from the 1st or 2nd to the 4th or 5th centuries)
- There is a higher antimony content in gunmetals and bronzes.
- Nickel-arsenic and nickel-antimony show positive correlations.
- A copper binding seems to have been silvered.
- There is a silver-tin plated brass strip.
- There is a tinned brass belt-plate
- A copper horse harness fitting was gilded, and a trifid horse-harness pendant was silvered.
- *Lorica segmentata* fittings tend to have smaller grains than other objects made from metal-sheet.

Kalkriese

- Dezincification of about 30% was found for almost all brass objects.
- Brasses have a mean of 21% zinc
- All brass shield bindings, except one, are primary brasses.
- One un-alloyed copper shield binding.
- Four *lituus* fragments are part of the same alloy or the same object. A total of seven *litui* fragments were analysed.
- Two group of objects form defined by arsenic content, but this is likely to be due to proximity to the limit of detection.
- There are two roughly defined groups by grain-size
    - In one of the groups (4 objects) defined by grain size, there were three objects from the group with higher arsenic content.
- Shield binding fragments have generally smaller grains that *litui*

All sites

- In brasses, zinc content tends to group in three ranges:

    - 20 to 22%
    - 16 to 18%
    - 8 to 10%, associated with gunmetals
- An inverse correlation of tin and zinc is seen, which is related to time period.
- No correlation between silver and lead was identified, which indicates that the lead used in alloying was not related to silver extraction.
- Objects from Kalkriese tend to have more nickel, except for a small group of objects from Kingsholm, which also show relatively high nickel contents.
- Objects from Chester have the highest manganese content, followed by Carlisle, but both with high dispersion.
- Object from Chester have the highest antimony content, whilst Kalkriese has the lowest.
- Antimony seems to be higher in bronzes, but this seems to be limited to later objects.
- Correlations between antimony and tin or antimony and lead were not identified.
- Four elements are implicated in the separation of the objects from legions *XVII-XIX* (from bivariate plots) from legions *II* and *XX*: nickel, cobalt, antimony and silver (arsenic could be contributing as well, but was not considered in the bivariate and multivariate analysis due to the lower precision of the measurements).
- The only trace element causing a relative separation between legions *II* and *XX* is silver.
- Objects from Chester and Kingsholm have smaller granular structures, indicative of a higher deformation in the last stage of cold working.
- *Lorica segmentata* grains are generally smaller than those of the shield binding fragments.
- PCA separates most of the Kalkriese objects and does not show separation between legions *II* and *XX*.
    - Component 1 is more influential (defined mainly by antimony, arsenic, and silver)
- Assuming three different military groups for LDA, the analysis classified 74% of the samples according to the *a priori* established groups.
    - LDA gave three separate centroids. The material from Kalkriese has the largest distance between groups, and the elements contributing to these separations are mainly nickel and antimony.
- LDA is capable of separating between groups of pre-analysis attribution when only considering brasses, bronzes or gunmetals.

5.14 Conclusion

This chapter presented the results of the analyses that constitute a metallurgical characterisation of the military equipment assemblages of this thesis. The following chapter discusses the results in the light of production processes and technological choices, visual appearance, place of manufacturing, recycling and identification with units. In the discussion the results are compared with the available published corpus of Roman metallurgy studies.

Chapter 6: Discussion

6.1 Introduction.

This chapter integrates the results presented in the previous chapter with the evidence available for the scientific analysis of Roman military equipment. First the equipment analysed is discussed in terms of alloy type (brass, bronze and gunmetal), comparing it with the available data on Roman alloys. Here, the pre-eminence of 'primary' brass in military contexts and the selection of bronze and brass to produce gunmetal with specific ranges of tin and zinc are discussed. A consideration of the presence and role of colour in military equipment follows. The effect of specific alloy compositions and plating techniques on colour parameters is also considered where technological choices are seen as subordinate to a need for display. Alloy-type analysis and grain size measurement combined show that some fittings from *lorica segmentata* could have been mass-produced, thus the possibility of mechanized production is considered. A brass ingot from Sheepen is considered as possible evidence for mechanized production and different stages in the manufacturing of military equipment.

Differences between equipment from the pre-Roman Iron Age are compared with the Roman objects analysed, in particular considering the trace elements. The results of the multivariate statistical analyses are discussed, and an explanation for the observed differences in trace element composition between the British objects and the objects from Kalkriese is given. The discussion sections are then integrated into a possible model of production and distribution for Roman military equipment during the first and second centuries.

6.2 Copper- alloy type

Of the objects analysed, more than 40% of them from the 1st and 2nd centuries are made of brass and the aggregate for all sites is 50%. Approximately 20% are bronze, 25% gunmetal and 5% copper. This is in broad agreement with the data from Roman objects (not restricted to military) from 1st and 2nd century northern Britain analysed by Dungworth (1995; 1997). Here, between 46% and 49% are made of brass, 28-31% bronze, 20% gunmetal and 4-9% copper. The slight difference between the two sets of analyses is due to a higher proportion of bronze objects in northern Britain. From the important site of Sheepen, near Colchester, Bayley (1985b) analysed 63 objects by x-ray fluorescence, identifying their alloy type. The objects, which belong to contexts dated from AD43 to AD61, comprise 44% brass, 24% bronze, 11% gunmetal and 8% copper. It can be concluded that the

proportion of alloy type across Britain tends to be consistent, at least in the case of military equipment.

Dungworth (1997) reports an increase in tin at the expense of zinc in copper over time. The same feature can be seen in the objects from Chester, which span from the late 1st century AD to the 4th. The well-known inverse zinc-tin relationship over time observed in both cases strongly suggests that brass and bronze were mixed, thereby producing gunmetal (Craddock 1978). The analysis of the Kingsholm objects presented here shows that this not only happened gradually over time, but brass and bronze were already being mixed in the mid-first century, the period in which primary brass use in Roman military equipment peaks.

6.2.1 Bronze

The use of bronze in military equipment exceeded that of brass in later periods, as not only are gunmetals frequent but also bronzes are more numerous than in the first and second centuries. Dungworth (1997: 908-9) reports that for later periods (from the third century on) the decrease in brass use is compensated for by the increase of leaded bronze and gunmetal objects (Dungworth states that 75% of the objects are leaded compared with two-thirds for the post-second century objects from Chester analysed here), and that other alloy types (such as leaded brass or leaded copper) are not common in any period. This behaviour in the proportion of alloy type has also been observed in Roman coinage, specifically in the brass *dupondii* and *sestertii*. The zinc content of these types of coins, originally high during the Early Empire (15-25%), decreased progressively from the second century until they ceased to be minted in the third century (Dungworth 1996).

Tin and zinc show structured distributions that are mostly defined by alloy type. If only bronzes are considered, the first broad peak of the bimodal distribution seen for tin (1st and 2nd centuries), at minor or trace levels, indicates brass with a high zinc content (Fig. 5.165). The second smaller peak is around 8% tin, which is the same value that Dungworth (1995: 97) reported for bronzes, at a level which can be considered intentional. This pattern of tin content in copper alloys however, is not exclusive to military equipment; analysis of Roman bronze lamps shows a diffuse distribution with a peak centred at 6-8% zinc (Hook & Craddock 1996: 146). This composition is a result of long recycling and metallurgical traditions and does not show particularly Roman features. In contrast, the pronounced very low tin content is probably a result of contamination of the copper by bronze.

6.2.2 Brass

In the dotplot Figure 5.164, the brasses show two higher concentrations of zinc, the highest at 21% and a second slightly lower centred around 18%. This latter figure is the most frequent value reported by Dungworth (1995: 97) for his northern British material. When brass contains over 20% of zinc it can be considered 'primary' (it has not been re-melted after the ingot was produced). A secondary brass, produced after re-melting brass, will contain between 15% and 20% zinc (Dungworth 1995). It can be said with confidence that both 18% zinc peaks found by Dungworth and the present analyses are caused by the presence of secondary brasses. However, only a fraction of Dungworth's data includes military equipment, which suggests that higher zinc concentrations are more frequent amongst military objects. Nevertheless, he reported that many of the first and second century sites from which the military objects came also included a high proportion of brass objects (Dungworth 1995: 152). The composition of 1st and 2nd century objects (personal use and domestic items) from the villa at Gorhambury, St Albans, also show a low proportion of brass (Bayley 1990: 138). At Camerton, where 1st century domestic and military objects were found, 65% of the military objects are made of brass, as opposed to 42% for the domestic objects (Cowell 1990). However, if brass brooches are not included in the domestic objects, only 20% of the domestic objects are made of brass. This supports the view that brass was mainly used for coinage, military equipment and specific types of brooches (often with military associations, such as the *Aucissa* type).

Hook and Craddock (1996) analysed 234 copper-alloy lamps from the first century AD, of which approximately 15% have zinc contents over 5%. Of these samples, only two are made of primary brass, and most of them contain 8% to 10% zinc (mixed with tin in gunmetal). Hook and Craddock (1996: 151) suggest that the brass used by the military was predominantly primary brass. Data from 15 brass military objects from Camerton (Cowell 1990) also show two zinc peaks for primary and secondary brass: 22% and 19% respectively. Secondary brass objects from non-military contexts could have been made by re-melting primary brass objects such as coins and military equipment (but a lower zinc content could be the result of significant amounts of tin and/or lead in the copper used for cementation, e.g. copper containing 3% tin would absorb 6% less zinc than if no tin were present [Craddock 1978: 12]). Secondary brass is the dominant alloy in some non-military contexts from post-Conquest Britain, suggesting deliberate acquisition (Bayley *et al* 2008: 48). The dominance of primary brasses in Roman military equipment is supported by the data from Ponting's (2002; 2006) analyses, which show a mean of 20% zinc for mid-first century military brasses from Masada and Gamla (Israel) with a distribution approaching normality (on a sample size of 60).

6.2.3 Gunmetals

If the distribution of zinc and tin of all the analysed gunmetals from Britain (dating from the first two centuries) is examined, it can be seen that three zinc concentrations stand out: 4-6%, 10-12% and 14-18% (Fig. 6.1). In the case of tin, one concentration is clearly dominant at 3-4% and there is a smaller peak between 6 and 8%.

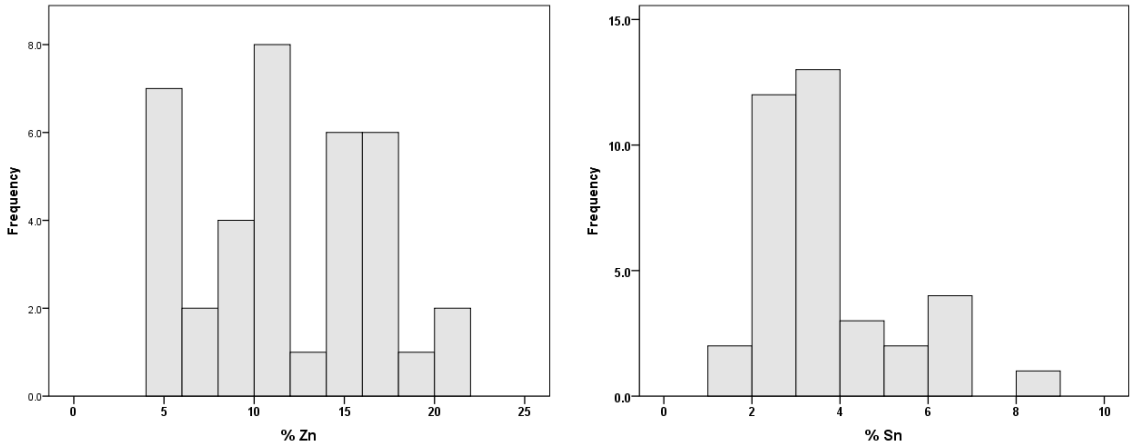

Figure 6.1 Distribution of zinc and tin for gunmetal objects from the 1st and 2nd centuries.

When the gunmetal objects are seen in a zinc v. tin scatterplot (Fig. 6.2) the samples tend to concentrate in four regions. The three zinc ranges mentioned above correspond to the 3-4% tin region, whilst a more spread 10-14% zinc area is related to higher tin contents (Table 6.1).

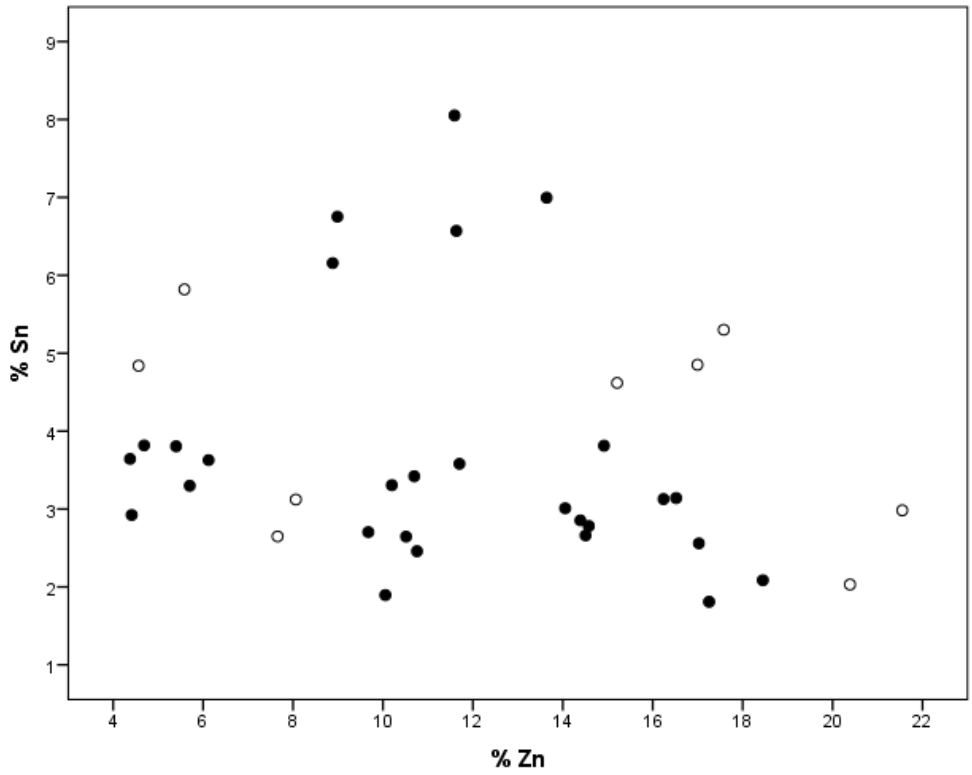

Figure 6.2 Bivariate plot of zinc v. tin content for gunmetal military equipment from the 1st and 2nd centuries.

Observed group	% Sn	% Zn
1	2 - 4	4 - 6
2	2 - 4	10-12
3	2 - 4	14-18
4	6 - 8	9-14

Table 6.1 Approximate ranges for gunmetal military equipment from the 1st and 2nd centuries.

Three of the groups from Table 6.1 generally fit with the inverse correlation that is seen between tin and zinc, which strongly indicates mixing of brass and bronze to create gunmetal. Another feature that can be seen from Figure 6.2 is the absence of gunmetal having tin contents between 4-6% tin and 6 to 14% zinc.

Even if the groups are not very clearly defined, the existence of a gap in the tin and zinc compositional range suggests that the combination of bronze and brass is not random. The groups seen in the plot seem to signify that there was planning behind the composition of the gunmetal of

the first and second centuries. The variability of tin content in bronze and the volatility of zinc (which has a greater effect on the final composition if the object is cast, as it implies additional re-melting) render futile any attempt to define a quantified model of how gunmetal was made beyond simple ranges. However, some qualitative possibilities can be suggested and the existence of structure suggests that there was some control in the ratio of bronze to brass.

Almost all the objects in groups 1-3 (Table 6.1) contain 2% to 4% tin and their tin content slightly increases as their zinc content decreases (Fig. 6.2). Group 3 shows the highest content of zinc (14-18%), which is similar to that of a secondary brass. This group could have been obtained by mixing bronze with primary brass or with secondary brass in higher proportions. In any of the two cases the ratio of brass to bronze employed is likely to be higher than a ratio of 1:1. Group 2 could have been obtained by mixing secondary brass with bronze, with brass as the dominant component or in approximately equal proportion to bronze. Finally, the objects of group 1 could have been obtained by mixing bronze with gunmetal, or bronze with brass with a high bronze-to-brass ratio (more bronze). Since tin tends to concentrate at around 8-10% in Roman bronze (Dungworth 1997) and the measured content for most gunmetal objects is between 2% and 4%, the proportion of bronze to brass is likely to have been 1:1 or less.

The group that contains between 6-8% tin and 10-14% zinc however, does not fit the inverse correlation and could therefore have been formed under various circumstances. The discrepancy with the correlation seen in the rest of the gunmetal objects (Fig. 6.2), in addition to having high contents of both tin and zinc, could have been obtained by a further addition of tin rather than solely being a combination of bronze and brass. Another possibility is that high zinc content brass was mixed with high tin bronze. However, the group could also have been formed by a combination of bronze with high zinc content gunmetal. Whatever the truth of the matter, it is clear that Roman military gunmetals were produced to distinct recipes.

Other examples of Roman military equipment made of gunmetal from other analyses from sites mentioned above suggest that Group 3 represents the most abundant combination:

- Haltern (3), all belonging to Group 3
- Camerton (3), all belonging to Group 3
- Masada: 1 object belongs to Group 2 and another to Group 3
- Gamla: 2, all belonging to Group 3

If the zinc and tin contents of civilian gunmetal objects from the 1st and 2nd centuries AD (Dungworth 1995) are also plotted (Fig. 6.3), the situation is very different. In this case, the gunmetal objects occupy a continuous broad band filling the gaps left by the military objects. An inverse correlation between tin and zinc can be clearly seen, but dispersion is very high when the zinc content is low. It seems that, in the case of civilian gunmetal objects, brass, bronze and gunmetal were indeed randomly mixed. This suggests a difference in the supply mechanism for recycled brass between civilians and the army, one where the military took greater care in selecting the alloys (mostly primary brass and bronze) of the objects that were re-melted to produce gunmetal with specific ranges of zinc content.

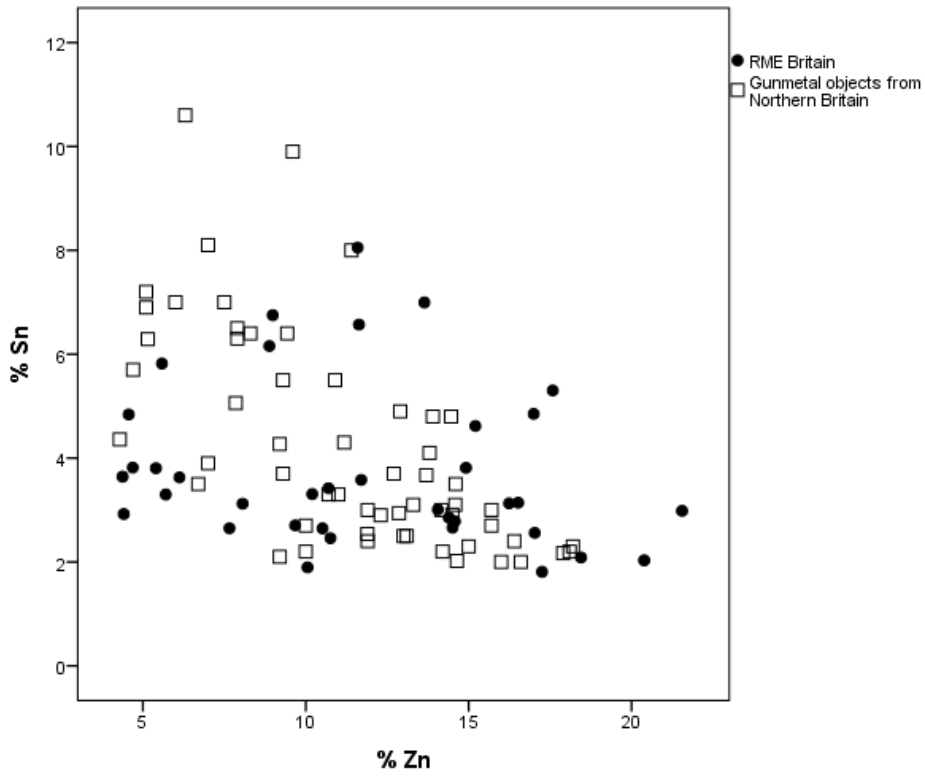

Figure 6.3 Bivariate plot of zinc v. tin content for gunmetal from 1st and 2nd centuries including civilian objects analysed by Dungworth (1995).

The technological choices made in order to obtain specific copper-zinc and copper-zinc-tin alloys do not seem to be related to the mechanical properties obtained with their use, but served as a means of enhancing group or individual visibility through ensuring bright and golden coloured metal fittings.

6.3 Colour

The use of colours by human beings as material metaphors is not an arbitrary behaviour, since colours are associated with substances and phenomena in a world that confers on them signifying qualities (Jones & MacGregor 2002: 11-2). Social meanings conveyed by colours are powerful because people feel with them rather than think with them (MacGregor 2002: 142). Colour can be applied to materials or be an innate property of them to achieve symbolism (Scarre 2002; 227).

Metallic Roman military equipment shows a combination of the two approaches in which the goal seems to have been to achieve the colour, shine and lustre that gold and silver confer to a particular surface appearance. This was made possible by the production of materials with specific innate colour qualities (copper alloys such as brass and specific gunmetal compositions) and technological processes to obtain desired colours and surfaces by the application of plating, such as tin, silver or gold.

The study of the use of colour in Roman military equipment has so-far been limited to the colour of the undergarments rather than the metal kit. For instance, the colour of the military tunic has been a topic of debate for years: military tunics have been traditionally considered white or red (Cowan 2003). However, Sumner (2002; 2009) suggested a wider variety of colours for the tunics of specific units in the Roman world since Republican times: Etruscan soldiers depicted on urns wearing red tunics, the mention by Livy (I*X*, 40,2-3; I*X*, 40,9) of Samnite soldiers wearing bleached white linen, as they had consecrated themselves as priests, or that naval personnel could have worn blue or grey tunics (Sumner 2009: 118-9). The *Notitia Dignitatum* (4th to 5th century AD) shows shields with colours and blazons associated to military units, and it is probable that such means of identification existed in the early empire as well, and could have been associated with specific cohorts or other units (D'Amato & Sumner 2009: 108).

Pictorial evidence has been seen as of value in terms of colour of equipment (Bishop & Coulston 2006: 20). In the Barberini Nilotic mosaic at Palestrina, Italy, which dates to between the first century BC and the third century AD, a centurion is shown with a white helmet, which probably represents silver or other white-metal plating (Fuentes 1987: 52). In the Judgment of Solomon fresco at Pompeii (earlier 1st century AD) a military figure standing in a pose of authority is shown wearing a white cuirass and helmet, in contrast to two other soldiers, who seem to be wearing bronze coloured armour (Fuentes 1987: 52-3) and Vegetius later mentions silvered helmets being used by centurions (*Epitoma rei militaris* 2.13). The colours remaining on the tombstone of centurion Caelius of *legio XVIII*, from the early Empire, were still visible in the 19th century and showed yellow *phalerae*

on a brown cuirass (D'Amato & Sumner 2009 127: 135) and finds of such fittings suggest that the yellow colour probably represented brass.

Brownsword (2004) reported that brass containing 15% to 20% zinc, or slightly less zinc if the alloy also contains tin, has a similar colour to that of gold. According to Fang and McDonnell (2011: 60), the brass that resembles gold the most is that containing 15% zinc. The most abundant groups (2 and 3: see Table 6.1) of Roman gunmetal military equipment analysed in this project, fall in these categories: Group 3, the most abundant, closely meets Brownsword's composition for a gold-like appearance. Fang and McDonnell developed a scientific method of measuring colour properties (developed from perceptible colour parameters such as brightness, hue and saturation). According to their data (2011: Fig. 6) it can be said that for gunmetal with 4% tin, which is a common composition in Roman military gunmetal objects, zinc contents of 6% and 10% (which correspond to Groups 1 and 2) also have a gold-like appearance.

The choice of brass and specific copper-tin-zinc alloys is of special interest in Roman military equipment in terms of visual appearance. These alloys visually resemble gold, a valuable metal that does not tarnish and has shiny reflective qualities, but at the same time they are harder materials capable of forming functional elements in the equipment, as seen in *lorica segmentata* fittings or *lorica squamata* scales. The use of brass in *lorica segmentata* fittings exemplifies, though, that the choice of brass is not ideal from the mechanical and chemical point of view. The archaeological record suggests high attrition rates for these fittings and reflects their low durability. As mentioned in Section 2.7, their coupling with different metal surfaces (iron plates and rivets made of different copper alloys) promotes bimetallic corrosion of the armour. It was, therefore, the innate colour of these copper alloys that was fundamental for their selection rather than their metallurgical properties.

A large number of military fittings were originally plated with a different metal. Iron helmets from the early Empire, for example, were often covered by a sheathing of thin copper-alloy sheet merely to produce visual impact (Bishop & Coulston 2006: 244). However, a more common feature is the tinning of equipment. The Romans probably took the practice of tinning copper alloy from the Gauls and used it during the early principate on helmets, scabbard and belt fittings, and armour (Bishop & Coulston 2006: 244). In Chapter 5 several examples of plating on the military fittings analysed were presented: parts of tinned brass *lorica squamata* from Ham Hill and Chester (HamHA1276 and CHE1834), a gilded un-alloyed copper roundel from Ham Hill (no accession number), a silvered *lorica segmentata* hinge from Usk (USKManF4N8), a tin-lead plated *lorica segmentata* tie-hook from Chester, a silvered copper binding and dagger frog, a tinned brass strip,

and a gilded horse-harness fitting from Kingsholm (GLC2136, GLC2943, GLC2357 and GLC538) and several tinned buckles and belt plates. All of these objects show a clear intent to obtain surfaces that looked similar to gold or silver. In the case of the gunmetal *lorica segmentat*a tie from Chester (CHE848, see Fig. 5.70) and a brass strip from Kingsholm (GLC2357, see Fig. 5.127), however, the tin-lead and the silver-tin plating, respectively, could be the remains of solder used to hold-on a silver foil rather than the remains of a plating *per se* (Lang & Hughes 1984). HamHA1276, which is part of a set of tinned brass scales alternating with scales left in their natural golden colour, makes a colour contrast when compared with an all tinned scale group from Hod Hill (D'Amato & Sumner 2009: 125).

Different shiny surfaces, but also other materials applied to obtain a matt finish, were employed to obtain visual contrast. In the case of iron objects colour contrast was achieved by inlaying objects with niello and silver for purely decorative purposes, as seen in iron scabbard chapes and slides from German forts (Bishop & Coulston 2006: 161). The choice of brass for diverse military fittings also allows the use of niello, which does not adhere well to bronze (Craddock 1978). The arrangement of the tinned brass scales from Ham Hill shows a particular array, in which tinned brass and non-tinned brass scales alternate (see Chapter 5). In this case, in addition to having purely decorative purposes, the pattern could have been used to differentiate between individuals or it could have been used to identify soldiers from particular units. An example of the use of metal contrast patterning being used for identification purposes was found at Dura-Europos, where copper- alloy rings arranged in the shape of a trident were built into an iron mail shirt of a Sassanian soldier (James 2004: 116; Fig. 55).

The importance of preserving the surface appearance is reflected in the technological processes used to apply it. The intermetallic compounds found in the tinned copper alloys analysed here, such as the brass *lorica squamata* from Ham Hill show that tinning consisted not simply of dipping copper alloys in molten tin (Bishop & Coulston 2006: 244), but also in the use of heat treatment applied after application in order to improve the adherence of tin to the copper alloy substrate (Meeks 1986).

Whilst certain types of the equipment could be individually customised or produced for individual soldiers, or even units, other types could have been fabricated on a larger scale and sent to different regions of the empire. The analyses suggest that it is probable that *lorica segmentata* fittings can be included in this latter group.

6.4 *Lorica segmentata* fittings

The great majority of the *lorica segmentata* fittings are made of brass, although there are a few gunmetal fittings from Kingsholm and Carlisle and gunmetal rosettes from South Cadbury Castle. Plate armour fittings represent approximately 1/3rd of the total number of brass objects analysed. With the exception of the fittings from Chester, which are dated to the late first century or the first quarter of the 2nd century, the brass *lorica segmentata* fittings analysed (all of them from Britain) show zinc contents centred around 20%. Bishop (2006: 243) also reported a composition of approximately 20% zinc for plate armour fittings and this is also the composition that Dungworth (1995: 11) reported. Dungworth (1995: 121) analysed eight *lorica segmentata* fittings, of which seven were made of brass, averaging 20% zinc. He commented on the possibility of them having been produced centrally by the state (or locally but following a centralised recipe) on the basis of the consistency of the zinc content. This idea is strengthened by the analyses of *lorica segmentata* from another part of the empire: 12 fittings from Gamla (Ponting 2002) show a highly consistent mean of 20.5% (relative standard deviation of 1%).

Not only is it probable that the brass used for these fittings was centrally produced, but also some of the objects themselves. To identify whether there is a link or not between places of metal production and object production of *lorica segmentata* fittings it is necessary to turn to the metallographic data. Of the 56 granular microstructures recorded for this project, 16 are from *lorica segmentata* fittings from different sites. If grain size is plotted against zinc content, a group can be seen in the upper left corner of the field of data points shown in Figure 6.4. This group is constituted by fittings having 20% zinc and approximately 10 micron grain size and shows very little spread (Table 6.2). All the fittings in this group are hinged elements (plates and buckle plates) and come from the sites of Usk, Kingsholm and Chester and date from the mid-first century, except for the fitting from Chester, which was found in a late first century context.

Sample	Description	% Zn	Grain size (microns)
USKManF3N7	*Lorica segmentata* lobate hinge	20.5	9
USKManF4N8	Hinged buckle	19.6	8
GLC48	Rosette object	20.2	8.8
GLC1533	*Lorica segmentata* hinged plate	20.5	10
CHE1513	*Lorica segmentata* buckle or strap attachment	19	7.3
GLC2378	*Lorica segmentata* hinged plate	18.8	9.1

Table 6.2 Group defined by grain size and zinc content of *lorica segmentata* fittings from the British sites.

It does not necessary follow that finding *lorica segmentata* fittings in forts indicates that the fittings were produced on that site. An example is provided by an industrial centre 385m from the fortress at Longthorpe, where iron working and bronze casting were in operation from the late 40s AD to 60-1 and military equipment was found including *lorica segmentata* fittings. However, these were probably scrap material instead of armour being manufactured at the site (Dannell & Wild 1987: 61).

In order to achieve the high level of reproducibility that the microstructure shows, a very controlled process of deformation from ingot to metal sheet would be required, the simplest way that this requirement could have been achieved would be by manufacture within a centralised production system. If *lorica segmentata* fittings were centrally produced (at least the hinged plate elements), such a large scale of production could also suggest a level of mechanized manufacturing.

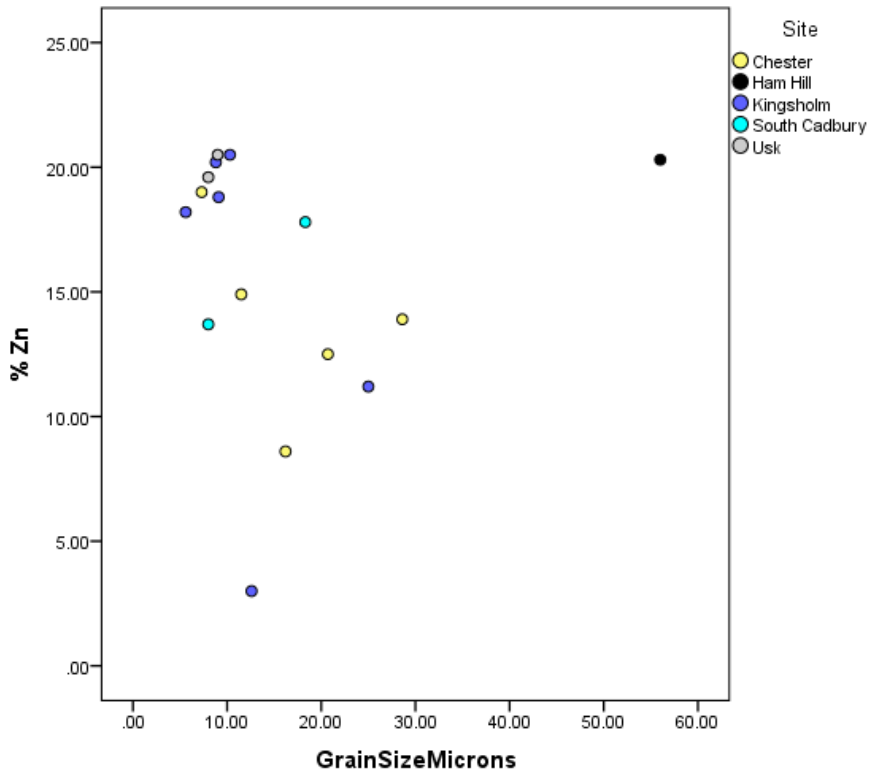

Figure 6.4 The relationship between zinc content and grain size (microns) for *lorica segmentata* fittings.

6.5 The possibility of mechanized production

After observing the uniformity of thickness of *lorica squamata* scales, Anstee (1953) commented on the high output that would have been required, and suggested that they could have

been formed by some type of rolling process. Sim and Kaminski (2012: 54) suggested that mechanical means such as passes through two crank-operated iron rollers could have been employed in the Roman world to produce metal sheets with very even sub-millimetric thickness. However, since it is generally thought that cast-iron was not produced before the Medieval period in Europe (the available furnaces were not able to reach a sustained temperature high enough to melt iron or low carbon steels [Tylecote 1992: 95]), any roller would have to be made of bronze. Nevertheless, Sim and Kaminski (2012) conducted an experiment in which three men could perform such a rolling operation. The process involved hot-rolling for reduction down to 1mm and cold-rolling for further reduction. Unfortunately the authors did not comment on the effects that rolling can have in the microsctructure of the metal.

Modern scholarship has often downplayed the role of technology in antiquity, outside specific areas such as construction or mining. This has been because most of the literary evidence was written for élites, who regarded technology and manual labour with contempt, and labelled as 'banausic', or mundane (Wilson 2002: 4). According to Wilson this attitude against technological innovation however, was not universal in antiquity and even some writers regarded technology highly; Plutarch considered mechanics as an art (*Marcellus* 14,4-6) and Vitruvius praised machine design inspired from nature (Vitruvius, *De arch.* 10,1,1-4; Greene 2008). The exploitation of water power provides an example of the inconsistency between literary and archaeological evidence in the invention of the vertical-wheeled mill, now believed to have happened in the third century BC and mentioned in Augustan times by Vitruvius and Strabo, but absent from the literature for the following 300 years (Wikander 2008). For instance, Wikander (2008: 142) mentioned evidence of *collegia* of water-millers in Phrygia and Bavaria (*CIL* 3.5866).

Diversification of the use of water-power for applications other than the water-mill, was already apparent by the first century AD and in the case of the Roman Empire, the army could well have been one of the factors responsible for introducing such technologies to the provinces, such as the bronze force pump from the copper mine at Sotiel Coronada, in Spain (Wilson 2008: 354). Those technologies would have soon become widespread in civilian contexts. Water-wheels could have been used to power hammers in forging operations in the same way that they were used for cutting stone and milling grain (Watts 2000; Lewis 1997), and there is literary and archaeological evidence for water-wheels being used to create a powerful sawing motion (White 1984: 56).

A thin sheet of brass could therefore have been produced by mechanised means and individual scales stamped from it by the likes of a fly- or screw-press. Screw presses were available in antiquity and were mentioned by Hero and Pliny (Hero, *Mechanics* 3; Pliny, *Historia naturalis* 18,

317; White 1984: 69-71) being used in fruit processing and for producing oil and wine. The use of such technology became common in the first century BC (Humphrey *et al* 1998; 154) and could have been used in many different applications. Crank mechanisms and bronze load bearing machine elements were also known in antiquity, as proven by the finds from the shipwreck at Lake Nemi, in Italy (Bunch & Hellemans 2004: 81; Rossi *et al* 2009: 170-1) and this technology could have been applied in sheet forming processes.

A brass sheet with a stamped inscription from Colchester, measuring 0.91 by 0.15 by 0.005m (Figs. 6.5 & 6.6), was found in a rubbish pit in a pre-Boudiccan context (at the site of Sheepen) along with large quantities of slag, furnace material, crucibles and scrap metal (Wright & Hassall 1971: 295). Analysis by Craddock (by AAS) showed a chemical composition of 72.1% copper, 26.8% zinc, 0.02% nickel, 0.14% iron, 0.05% antimony and 0.007% silver (Musty 1975: 410). This brass was never re-melted and it is a good indicator of how close the zinc content could be to the theoretical maximum of 28% that can be obtained by the cementation process. Other brass ingots that have been found have lower zinc contents (Bayley 1998): 20.6% zinc (from Claydon Pike, upper Thames), another of similar composition from a wreck of the coast of Corsica, and ingots containing 20.3% and 18.9% zinc (both from Gloucester).

Musty (1975: 410) mentioned that metallographic analysis had been performed on the Sheepen ingot, revealing "...a well-homogenized and worked solid solution with twinned grains and a hardness of 97 HV... with little sign of final cold work in the centre of the specimen", but no micrographs accompanied the publication. The description however, seems to point to a regularity of the bulk microstructure after cycles of annealing and working.

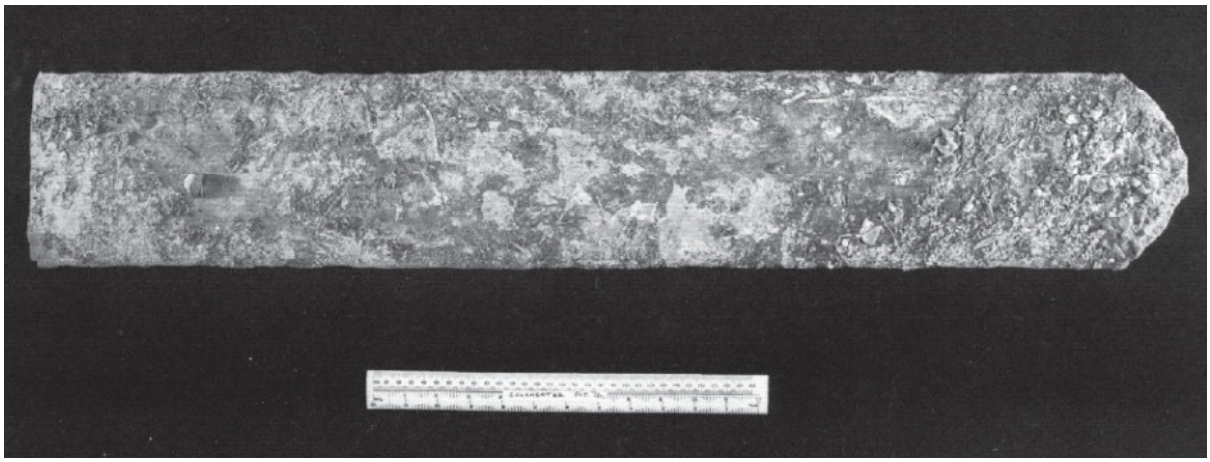

Figure 6.5 Primary brass sheet from Colchester: 27% Zn (Niblett 1985).

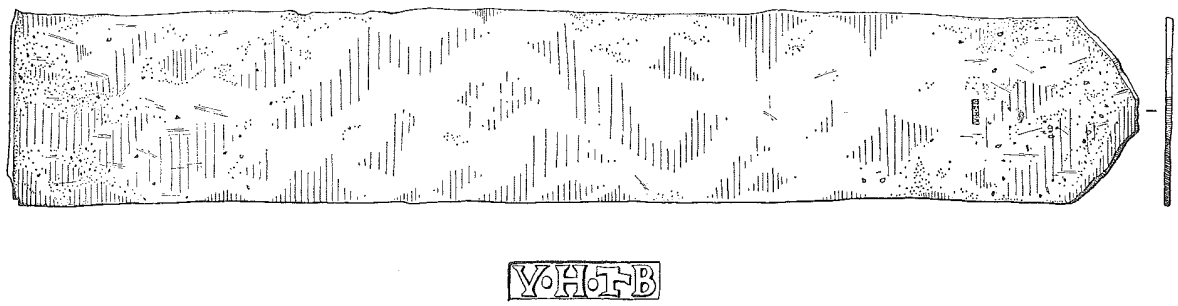

Figure 6.6 Drawing of the same plate with inscription: VH-ET-B (Musty 1975).

One of the ends of the strip (the right end in Fig. 6.6) looks very similar to an end of a rolled strip after consecutive passes. The strip shape after a theoretically ideal rolling process, when internal stresses are equal across the width of the strip, would be rectangular. In practice however, several rolling defects are normally seen to varying extents giving rise to different strip shapes, in the metallurgical literature such shapes are referred to as latent, manifest, dual, or affected by tension (Fig. 6.7; cf. Ginzberg 1989: 567). In a latent shape, which shows an end very similar to that of the strip from Sheepen, the stresses are not equal across the width of the strip, but it is still able to resist the formation of buckles along its surface. A flat surface would then be expected for a strip with a latent shape. It is therefore important to note that there are no visible undulations on the sheet metal from Colchester.

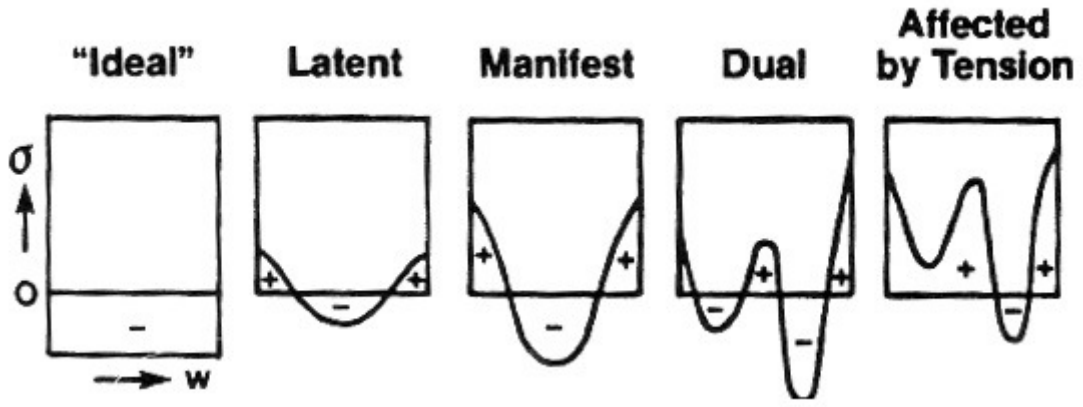

Figure 6.7 Form of strip shape with stress distribution (Ginzberg 1989: 576).

As part of a recent study, a hot- and cold-rolled ingot, processed in the manner of a reversing rougher mill (reversing by longitudinal direction after each pass) was formed into a strip 1mm thick (Fernández Reyes 2007). The geometry of the end of the strip (Fig. 6.8) closely resembles that from the ingot found at Sheepen. The 'latent' strip shape is more pronounced since it underwent greater thickness reduction (down to 1mm rather than 5mm) and in the case of the

rolled strip in Fig. 6.8, the metal used was an aluminium alloy. Rolling this alloy would change operational parameters and would produce different microstructural effects, but does not change geometrical conditions defined macroscopically in the rolling process, such as the 'latent' strip shape as a probable outcome.

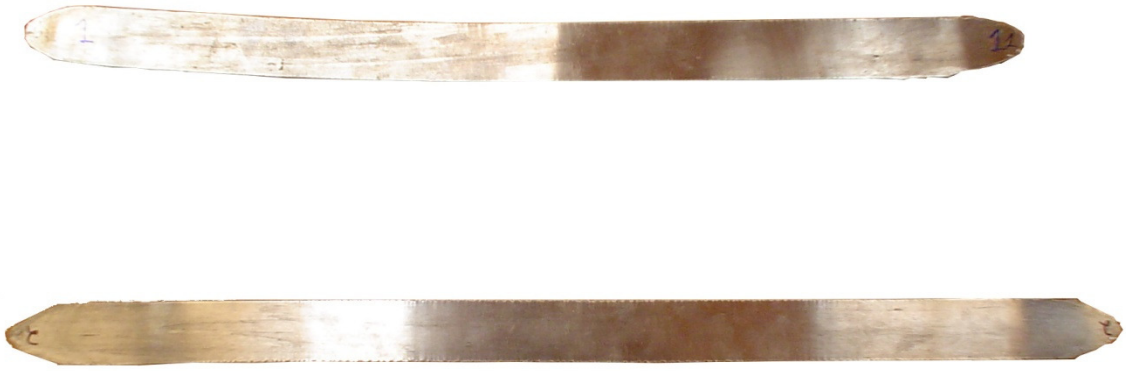

Figure 6.8 Strip shape after hot and cold rolling down to 1mm thickness.

In the example from Sheepen, the strip shape and the reported difference on evidence of cold work between the centre of the cross section (less strain) and the rest of the cross section are compatible with the proposition of a mechanised process such as rolling (Zhu *et al* 2007: 765). However textural analysis of the microstructure, which would be able to identify preferred crystal orientations across a transversal section of the strip, is the only way to irrefutably establish whether the strip was rolled.

The sheet bears an inscription of unknown meaning VH-ET-B, (RIB 2407; cf. Collingwood & Wright 1990) which seems to be stamped after processing, and could be related to the workshop that formed the metal strip. Its presence has an important implication: metal sheet, an intermediate stage between an ingot and a finished object, was produced and transported to a different place, where objects were manufactured from it. In addition, the place of production of the sheet from Sheepen could have been different to where the ingot was made.

The state could have controlled all the primary brass input to Britain and sent to private companies having contracts with the army. In parallel the army could have also produced equipment itself in addition to repair work in *fabricae*. Other sheet-metal based objects, required in large volumes such as shield binding, could also have had mechanized production as part of their fabrication history.

6.6 Shield binding

Shields were a crucial element in the Roman army fighting technique as both defensive and offensive weapons. The binding around them, which was attached by means of copper rivets, was usually made of brass. Binding must have had a high attrition rate even if it was generally harder than other brass objects due to cold-working and a small grain size.

Shield binding is very thin and its microstructure generally shows a high degree of deformation due to cold work in the last stage of its fabrication. Even if mechanized production had been used at some point during the process to reduce the thickness of the sheet from which the shield binding was made, the last cold work processing would have to be done by hammering. This last stage would alter any previous microstructure reflecting mechanized production, resulting in the heavily deformed and irregular microstructure that is observed.

6.7 Trace elements

As was mentioned previously (Chapter 2), analysis of Roman military equipment, especially including trace elements, has been scarce (Craddock *et al* 1973; Craddock and Lambert 1985; Cowell 1990; Riederer 2002; Ponting 2002; 2006). In some instances the analytical techniques that were used are not able to detect some elements at a level of accuracy or precision that allows for comparison, as was the case for nickel and cobalt in Dungworth's analyses (1995), because the technique used was ED-XRF (a technique better suited for major and minor elements). However, those analyses that do use trace element techniques such as AAS or ICP-AES can usually be compared qualitatively with the data presented in this thesis. Some of the analyses reported include Iron Age objects contemporary to the Roman conquest, which provide a useful comparison (Cowell 1990; Northover 2000).

6.8 Comparison with non-Roman copper alloys

Iron Age copper-based alloys tend to be bronzes only, and it was not until the arrival of the Romans that brass was widely introduced to Britain (Craddock 1978). However, there are also differences in the trace elements present between the copper alloys from both periods.

Roman military equipment from the conquest period is distinctive from that of the indigenous population (Late pre-Roman Iron Age) in southern Britain. As observed in Chapter 5, there is a significant difference between samples associated with *legio II* and those associated with

legio XX in only a small fraction of cases. For the purposes of comparison with other analyses they can therefore be considered as a single group, because their trace element concentrations (nickel, cobalt, antimony, silver and arsenic) show similar behaviour when they are considered together. Military objects from Late Iron Age and Roman contexts from the site of Camerton were also analysed by AAS (Cowell 1990) and it can be seen that the material from the LIA contains greater quantities of nickel and also shows a tendency for higher levels of cobalt than the Roman objects (Fig. 6.9). The Roman military equipment from Camerton generally fits into the core of the group defined by the samples from legions *II* and *XX* analysed here.

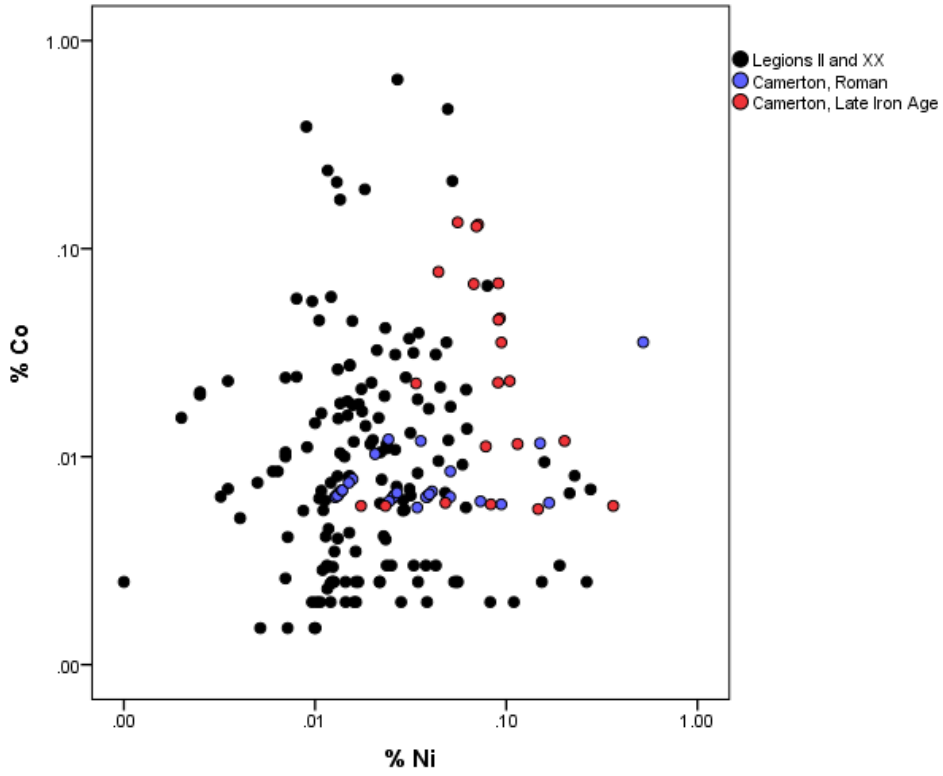

Figure 6.9 Bivariate plot of nickel and cobalt (rescaled to the copper) of military equipment from Camerton (Roman and Late Iron Age) compared to the analysis of legions *II* and *XX*.

Northover (2000) analysed Late Iron Age un-alloyed copper shield bindings from Cadbury Castle down to trace element level. Although he used an electron microprobe with wavelength-dispersive spectrometry and therefore not directly comparable with AAS, it can still be seen qualitatively that the Iron Age material is clearly distinctive from that of the Roman equipment. Again, as in the case of the contemporary military equipment from Camerton, the Iron Age bindings show significantly higher levels of cobalt (Fig. 6.10) and nickel (Fig. 6.11).

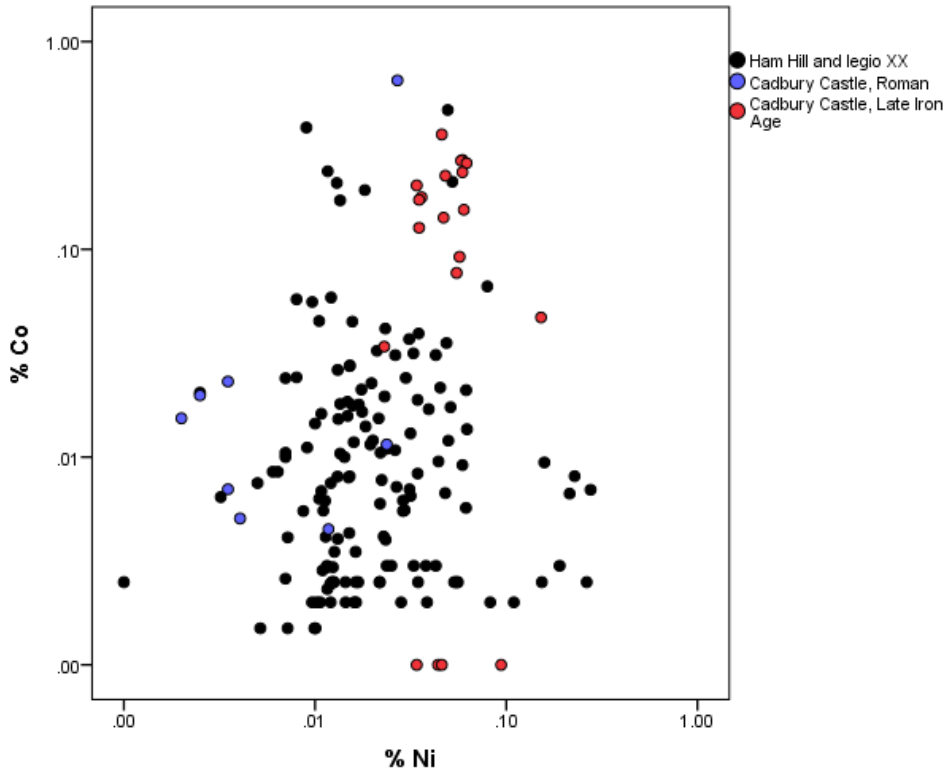

Figure 6.10 Bivariate plot of nickel and cobalt (rescaled to the copper) of Late Iron Age copper binding compared to the analysis of legions *II* and *XX*.

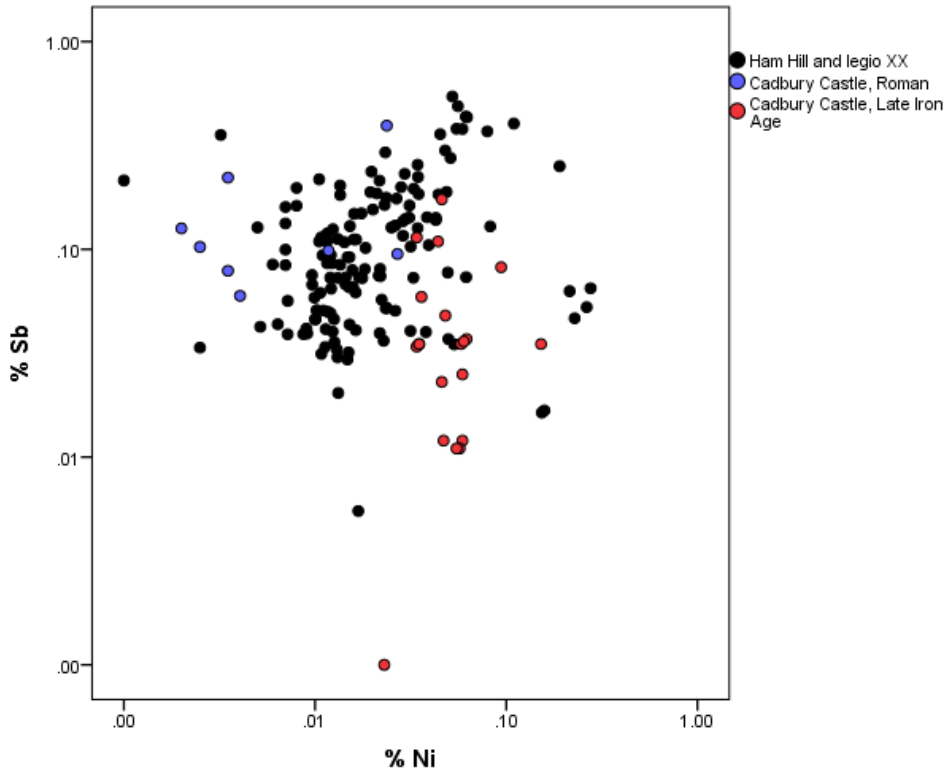

Figure 6.11 Bivariate plot of nickel and antimony (rescaled to the copper) of Late Iron Age copper binding compared to the analysis of legions *II* and *XX*.

Dungworth (1995: 78) also noted higher concentrations of nickel in Iron Age objects when comparing Iron Age and Roman (mainly 1st and 2nd centuries) copper alloys from northern Britain, but his study did not determine cobalt for the Roman alloys. Differences in nickel and cobalt between Roman and Iron Age copper alloys are probably due to the use of different copper sources, but they could also be associated with differences in technological process, such as the furnace atmosphere (especially for cobalt: see Chapter 2).

The analyses showed that some of the Kalkriese objects could not be Roman. Three of the Kalkriese objects analysed were found at locations some distance from the 'Oberesch' site, where all the other objects of the assemblage were found (Wilbers-Rost 2014, *pers. comm.*): K1318143-S6 in site 13/8/143, K186 in site no. 13/8/139 (a few kilometres west of the Oberesch) and KProsp6_29/6/102 in site no.29/6/102 (to the east). K1318143-S6 is a crest knob from a *Coolus* type of helmet and is made of leaded copper. This material is not unusual in this type of object since the lead was added to facilitate and improve the casting. The remaining two objects found outside the Oberesch site are K186, an un-alloyed copper sheet and KProsp6_29/6/102, a shield binding fragment also made of un-alloyed copper. The material of this shield binding is noteworthy, since all the other shield binding fragments from the Oberesch (and from the British sites) are made of brass.

When trace elements are examined for these samples (Figs. 6.12 & 6.13) it can be seen that the helmet knob (K1318143-S6) is very similar to the rest of the objects from the Oberesch and the sample belongs to the bulk of the assemblage in both plots. On the other hand, the sheet metal objects K186 and KProsp6_29/6/102, have significantly more arsenic and antimony than most of the samples from the Oberesch site. These two objects also contain larger quantities of silver, and in the case of K186, also a higher level of nickel than the objects from the Oberesch site.

Whilst the helmet crest knob is clearly Roman, both on compositional and stylistic grounds, the sheet fragment and the shield binding seem to belong to a different metallurgical tradition and therefore are probably of indigenous Germanic manufacture. These two samples are made of a different alloy type (the sheet metal from Kalkriese seems to be brass) and are significantly different in their trace element pattern.

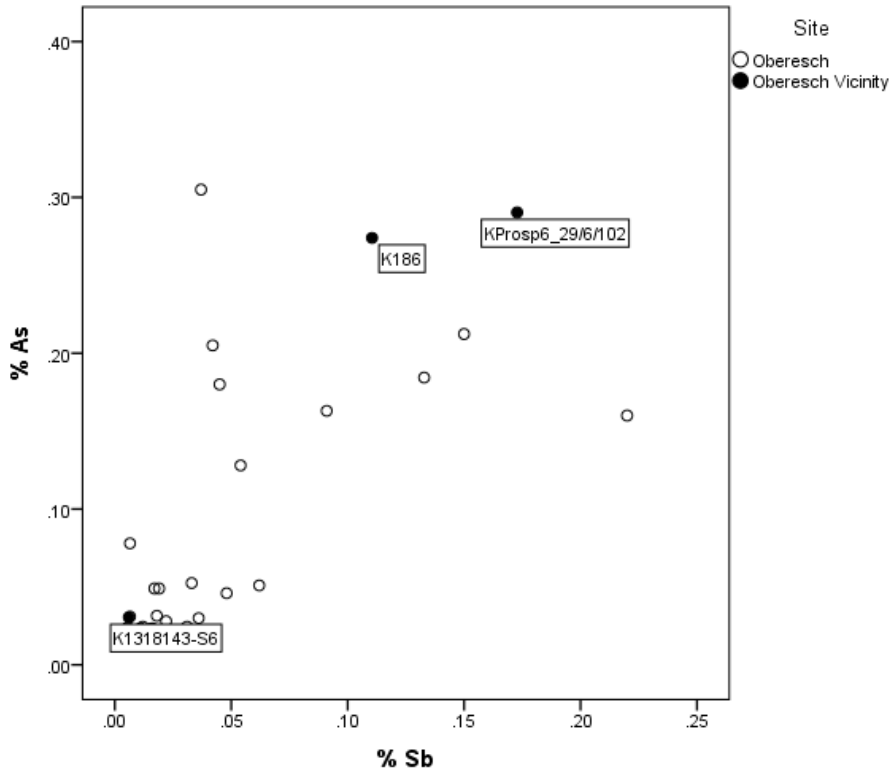

Figure 6.12 Bivariate plot of arsenic v. antimony (rescaled to the copper) showing objects from Kalkriese that do not belong to the Oberesch site.

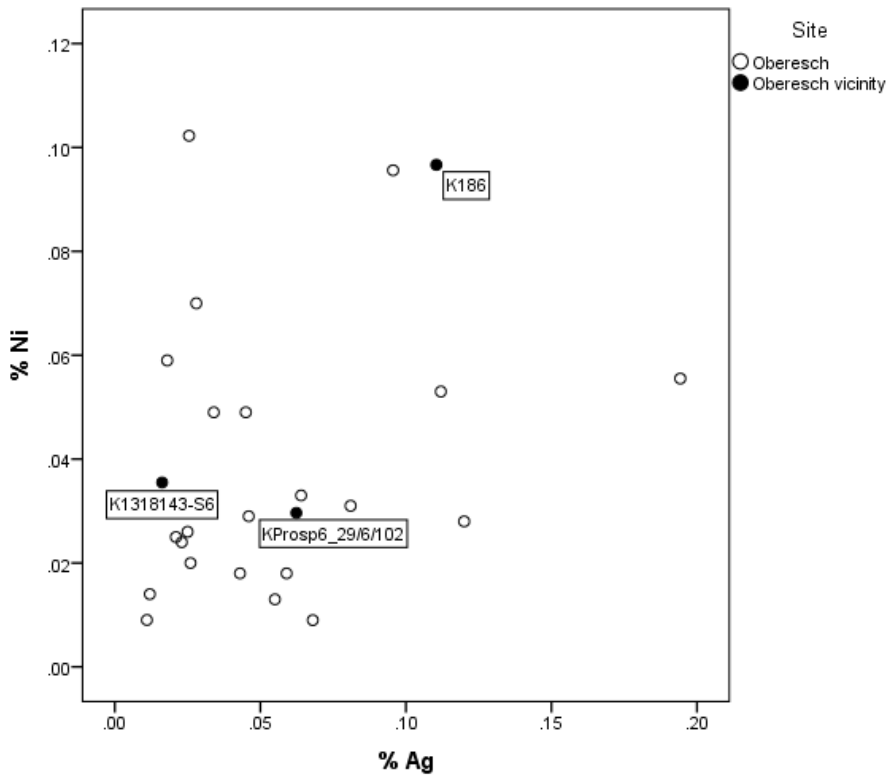

Figure 6.13 Bivariate plot of silver v. nickel (rescaled to the copper) showing objects from Kalkriese that do not belong to the Oberesch site.

6.9 Legions *II* and *XX* and the difference of their equipment to that from Kalkriese

6.9.1 Recycling pools

For millennia, metal was a unique material due to its inherent recyclable qualities that allowed for re-melting and re-working; recycling must have occurred from the advent of metallurgy. As seen in Chapter 2, some of the trace elements in copper are more prone to remain in the metal with their content virtually unaltered by re-melting, whereas others are greatly changed. However, re-melting and the addition of different metals would obscure the original quantities and proportions of trace elements in the copper. Nevertheless, a relatively homogenous input of raw material would have created a recycling pool with some characteristic compositional ranges for the trace elements more likely to survive the metallurgical processes, even when different sources of copper were mixed.

Bray and Pollard (2012) show how the successive re-melting of copper alloys from a single source can be tracked by a gradual depletion in the concentration of elements (related to the copper) that are more prone to oxidation. Antimony and arsenic are examples of such elements. In their study, Bray and Pollard tried to assess the degree of recycling of Bronze Age axes and daggers from the British Isles. They calculated the number of re-melts by measuring the decrease in arsenic content of the objects based on the assumption that most of the copper for the bronze was supplied by a single mine: Ross Island, Ireland.

If brass was centrally produced, the copper used to produce it could still have come from diverse sources, especially over long periods of time. If a period of time of only a few decades is considered however, a relative homogeneity of the copper composition for the single source of brass could be assumed. Tracking recycled metal from an original single source would however, become unviable if the recycled metal is mixed with external inputs (from a different source or even from the same source at a different period of time).

The inputs of a recycling pool are complex and could have presented themselves simultaneously. Local inflow of copper alloys as part of recycling within the army could include, for example, what Bishop (1985a) calls the ‘hoard-core,’ or scrapped equipment. Alternatively, another internal input could be metal being recycled by private manufacturers. These two internal subsystems are likely to have been open to each other, so that the result is a diffuse large group that only changes significantly when long time periods are considered or by large external inputs.

External inputs could be centrally produced copper alloys or scrap material from any source. The effect of mixing and recycling equipment of different types and life-spans would be dampened if large numbers of objects are considered. The characteristic patterns of a recycling pool would change gradually unless a sudden surge of large quantities of different material entered the system. An analogous sudden input of material could be production of new equipment on a large scale in anticipation of a military campaign, such as the conquest of Britain.

6.9.2 Legions *II* and *XX* between the mid 1st century and the early 2nd century

The objects belonging to the soldiers of legions *II* and *XX* could be considered as constituting, or at least forming part of a recycling system. The contexts from which the objects from legions *II* and *XX* originate span approximately 60 to 80 years (excluding the late Roman objects analysed). In such a period of time the alloys could have changed in their trace element composition from that of the immediate conquest period. In order to determine whether there was a significant change over this time period, trace elements of objects from Carlisle and from the early phases of Chester were plotted against each other. Figures 6.14 and 6.15 show that there is no noticeable difference between the objects from Carlisle and Chester and the rest of the legion *II* and *XX* objects considered together. This suggests that there was not a large input of material into Britain between the conquest period and the first half of the 2nd century.

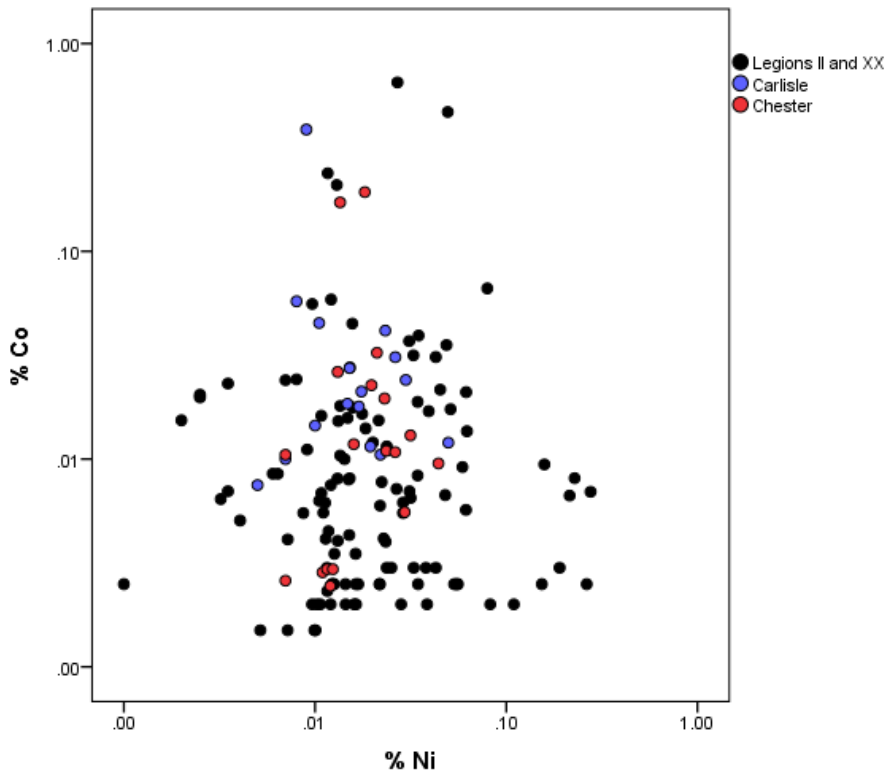

Figure 6.14 Bivariate plot. Nickel v. cobalt from Carlisle and Chester with the legions *II* and *XX* objects.

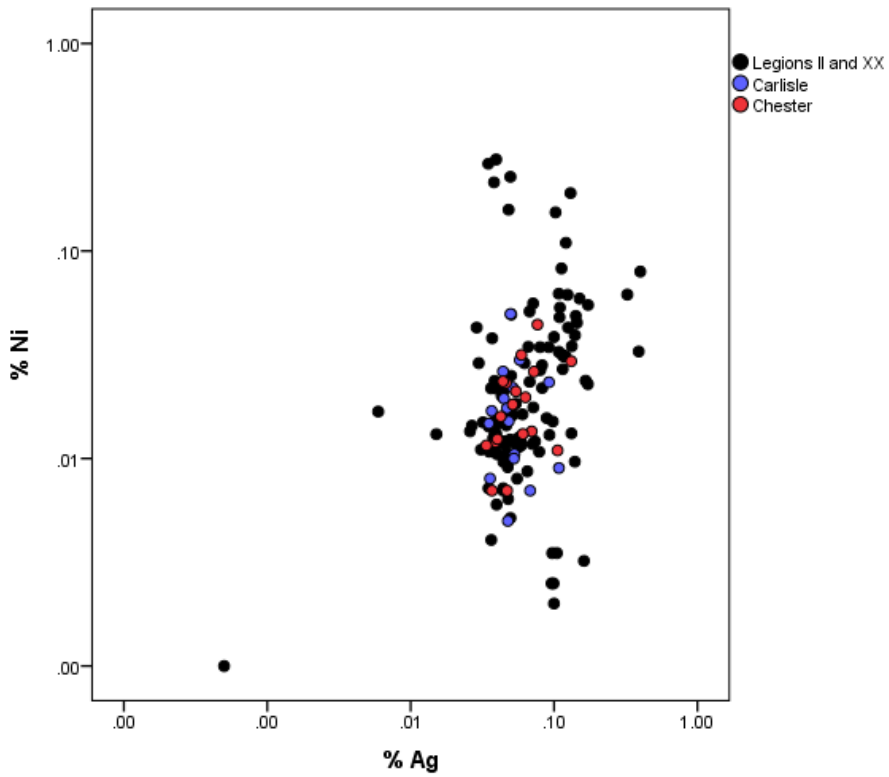

Figure 6.15 Bivariate plot. Silver v. nickel from Carlisle and Chester with the legions *II* and *XX* objects.

It can also be concluded that the consistency of Roman metallurgical practices during the 1st and 2nd centuries AD in terms of the main alloy constituents and proportion also affects the distribution trace elements. This is probably the result of a large but relatively closed recycling system within Britain.

6.9.3 Local differences in legions *II* and *XX*

Even if the aggregate objects from legions *II* and *XX* are very similar when trace elements are considered, some differences can be seen on a site level. Some of them are due to temporal differences, but there are others that seem to appear in accord to alloy or unit type.

In the case of Chester, where bronzes (very often leaded) became the main alloy type after the second century, the higher nickel and silver content in later material reflects the changes in the recycling pool of copper alloys after one or two centuries. The late first and second century objects show a trace element composition very similar to the rest of *legio XX*.

The eight objects from Kingsholm (six made of brass and two of gunmetal) with distinctively higher amounts of nickel (an element related to copper and very reliable to analyse by AAS) were all made from sheet metal and are mostly *lorica segmentata* fittings and binding fragments. These objects do not constitute a group, since their dispersion in all the bivariate plots is very high however, the copper from which they were made must have had very different origins to that of the rest of the objects in the assemblage and therefore indicate a different workshop or recycling pool.

At Carlisle there seems to be a difference between the military units in terms of the source of the metal for their equipment, based on trace elements. The group defined by higher arsenic and antimony levels mainly comprises horse harness equipment (Fig. 5.24) and so could be related to the *ala Gallorum Sebosiana* or the *ala Petriana*, which were present at Carlisle in the late 1st century and early 2nd century respectively (Howard-Davis 2009; Breeze 2006). This separation is supported by the correlation of some of the gunmetal objects found, none of which are horse-harness fittings.

6.9.4 The preparation for the invasion of Britain

The assumption of four legions in the invading army of AD43 (*II Augusta, IX Hispana, XIV Gemina, XX Valeria Victrix*) is based on the presence of four legions in the province by the time of the Boudiccan rebellion in AD60, but the only named legion in literary sources is *legio II Augusta* (Hoffman 2013: 67). Since Gaius' two new legions *XV* and *XII Primigenia* were not experienced, *II Augusta* and *XIV Gemina* were brought to the invasion of Britain from the Upper Rhine, *XX Valeria Victrix* from the Lower Rhine and *IX Hispana* from Pannonia (Holder 1982: 15; Levick 1990: 141).

It seems that Gaius had already prepared for the invasion of Britain in AD39, where he mustered a large army in Lower Germany, but this was aborted (Holder 1982:15). It is likely that preparations for the invasion were made during this time (or fabricated shortly before for the German campaign) and would have included the manufacture of military equipment; this stock-pile of materiel would have been available for the Claudian campaign of AD43. Troops had been moved to Gaul prior to crossing The Channel, and these units carried siege equipment (Suetonius, *Caligula*, 46), and it is likely that some of the supply channels prepared in AD40 were still open three years later for the actual invasion (Salway 1981: 60-1). The arrival of legions represented a large flow of copper-alloy equipment into Britain and a significant amount of that metal, recycled or still as military equipment, would be extant decades after having a continued presence in the available recycling pool of copper alloys.

6.9.5 Kalkriese and Haltern

With three legions known to have been lost in the Varusschlacht, it is reasonable to assume that those units would have been present at Kalkriese (see Section 4.7). However the analysis did not identify any chemical differences that could suggest different units were represented within the group of objects analysed. This may suggest that all three legions were supplied by the same workshops or that their metal supply came from the same recycling pool or that it was just one unit. Alternatively, the sample size of the analysed objects could have been too small.

One of the three legions destroyed at Kalkriese, *legio XIX,* is attested epigraphically at the important early Roman fort-base at Haltern on the Lippe (von Schnurbein 1974; Bishop 2012: 73) and at least part of it could have been based there before the Varian disaster of AD9. It is not yet known whether Haltern was definitively abandoned in AD9, or if the fortress was re-occupied by the Romans during the campaigns of Germanicus, between AD10 and 16, after which the entire area was vacated (Moosbauer 2009: 96). Thus, the objects from Kalkriese and Haltern can be considered contemporary.

Military objects from Haltern, an assemblage dominated by horse harness equipment and buckles, but also including *lorica segmentata*, helmet and scabbard fittings, were analysed by Riederer (2002). The analytical technique was also AAS and included the measurement of silver, nickel and antimony as trace elements. The objects from this analysis were compared with those from Kalkriese by using DA and MANOVA.

One of the two groups that form when grain size is taken into consideration (formed by four objects in Fig. 5.162) contains three of the shield binding fragments with a detectable content of arsenic (Fig. 5.146). Since arsenic is not an element for which AAS has high precision, it is not possible to establish whether the two apparent groups of shield binding (seen as just above or below the detection limit) reflect a real difference between two groups of objects or is merely an analytical effect. If the group is real it could mean that the metal was produced and worked in a different workshop, or that it belonged to a different legion, or both.

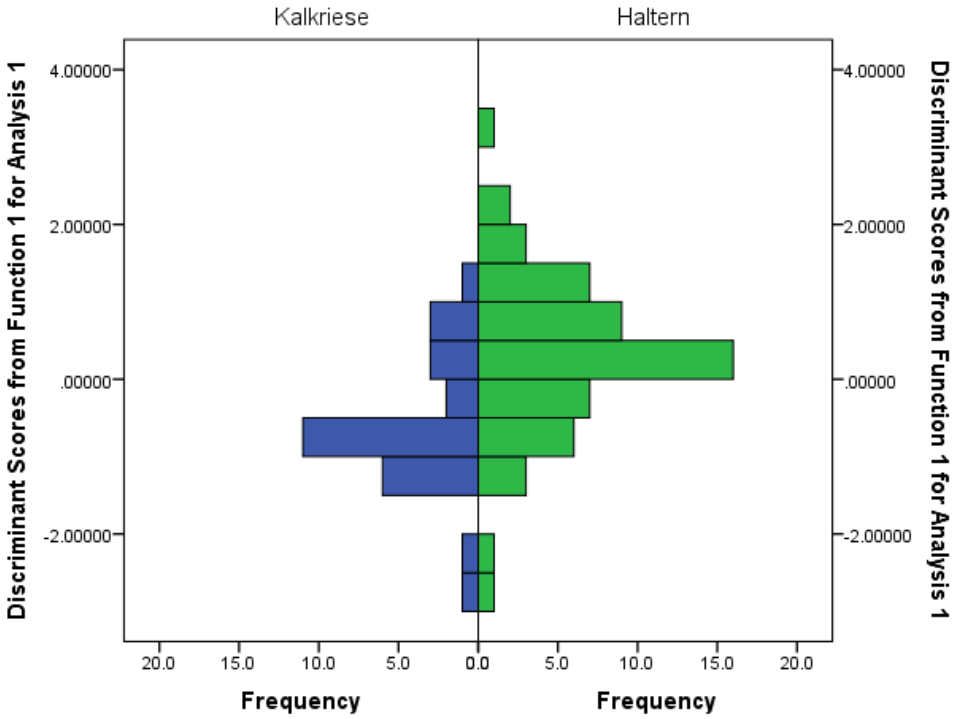

Figure 6.16 Discriminant scores plot of military objects from Kalkriese and Haltern.

The results of the analysis of the equipment from Haltern however, might not be directly comparable with the analysis of the objects from Kalkriese using multivariate statistics, due to differences in limits of detection and analytical protocols. Nevertheless, if the two data sets are compared by plotting the computed discriminant scores (Fig. 6.16), there is a large area of overlap between the two sites with the scores of the objects from Kalkriese slightly shifted to the negative numbers of Function 1. According to the function coefficients computed by discriminant analysis, this difference corresponds to the elements silver and antimony. Silver contents are slightly higher for the Haltern assemblage, and antimony levels are slightly lower for the objects from Kalkriese.

MANOVA showed, using Pillai's trace criterion based on silver, antimony and nickel as dependent variables, that there is a significant separation for only 16% of the combined data of the two assemblages. It can be concluded, therefore, that the trace element compositional data for the objects from Kalkriese and Haltern are very similar.

If it is accepted that the two datasets are comparable, then the conclusion must be that these two assemblages are almost identical in terms of their chemical composition and that therefore the metalwork from Haltern and Kalkriese was made from the same metal, or, probably more correctly, metal drawn from a shared supply (either freshly smelted metal or re-cycled scrap).

As seen above, the samples from Camerton are considered to belong to *legio II Augusta*, since they are probably associated with the conquest of south-west England under Ostorius Scapula (Webster 1958; Jackson 1990; Brewer 2002b). A discriminant plot considering legions *II* and *XX*, together with the objects from Haltern and Kalkriese shows the centroids of legions *II* and *XX* to be close to each other, and clearly distant from the group formed by Kalkriese and Haltern (Fig. 6.17).

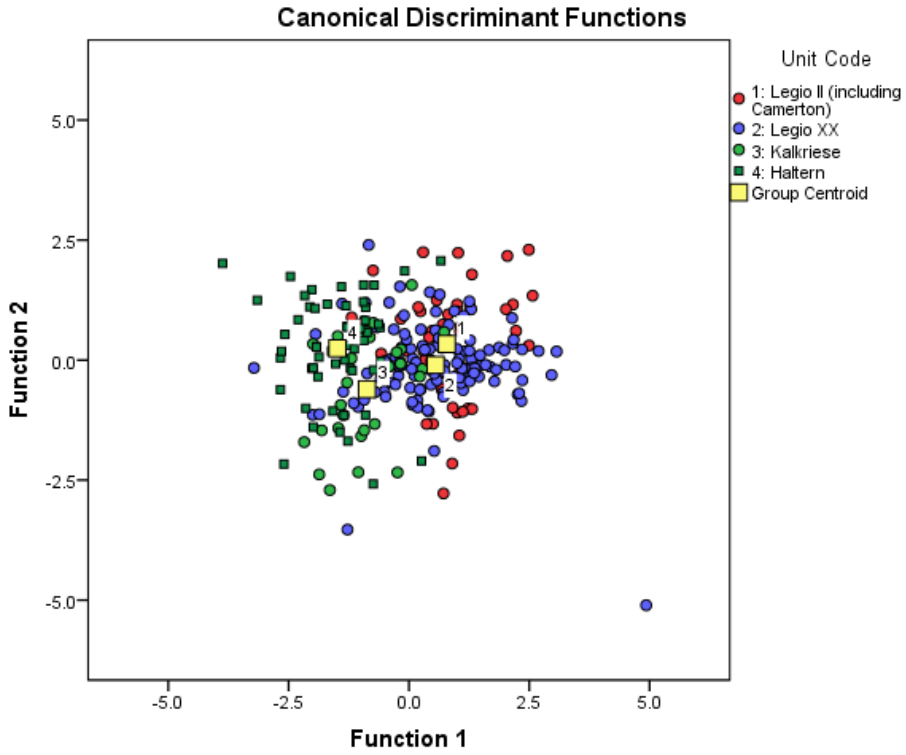

Figure 6.17 Discriminant scores plot of military objects from legions *II*, *XX*, Kalkriese and Haltern.

As seen in Section 5.12, trace elements (mainly nickel and antimony) in the British material are different in their trace element composition from the Kalkriese objects. This suggests that:

a) a different copper supply was used to make the brass for units in Britain
b) the difference in the trace element pattern is a result of a time separation of six or seven decades between the fabrication of the equipment from each region.

Both possibilities could be combined and related to a wave of production of military equipment in anticipation of the conquest of Britain compared to equipment that could have been produced years before the events at Kalkriese.

6.10 Masada and Gamla

Comparative chemical data from mid-first century AD material is available from a different part of the Empire: the sites of Gamla and Masada in Israel (Ponting 2002; 2006). In these cases the analysis was performed by a different technique, ICP-AES, a trace element technique with higher sensitivity and precision than AAS. However, the standard reference materials utilised are the same as those employed for this thesis and thus provide a reliable basis on which the two sets of analyses can be compared.

A comparison between the trace elements (silver, nickel, cobalt and antimony) of the equipment from legions *II* and *XX* considered together, the legions of Kalkriese and the military objects from Masada and Gamla can be seen in Figure 6.18. It is clear than the objects from Masada are very similar to those from legions *II* and *XX* and those from Kalkriese, except for a small group with more negative values along the vertical axis. The group comprises two figurines and a number of scabbard frogs, in contrast to the rest of the assemblage, which is populated by *lorica segmentata* ties, dagger scabbard chapes, apron terminals, shield binding and equine equipment. This small group is formed by objects made of bronze and un-alloyed copper, no brasses are present. In a bivariate plot, it can be seen that this group separates from the rest due to higher levels of silver and nickel (Fig. 6.18).

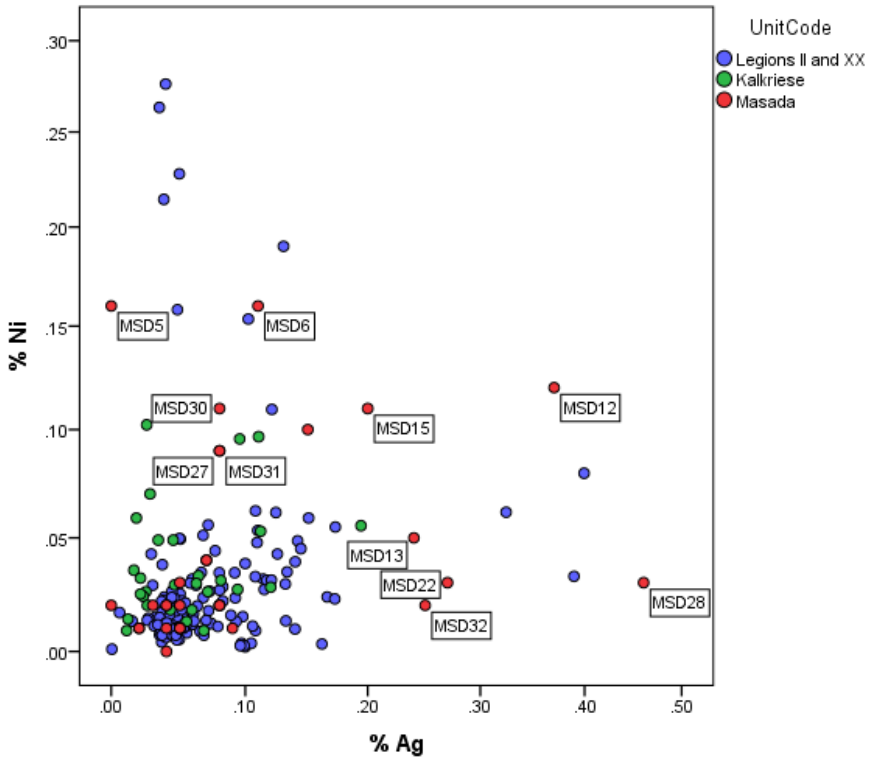

Figure 6.18 Bivariate plot. Silver v. nickel of objects from legions *II* and *XX* shown with military equipment from Kalkriese and Masada.

In contrast, most of the objects from Gamla are very different from any of the analysed equipment from legions *II* and *XX* that was analysed or the group from Kalkriese as can be seen from the separation along the horizontal axis (Function 1 in Fig. 6.19). The main element causing this separation is nickel, the dominant element in Function 1. As can be seen in the bivariate plot (Fig. 6.20) the objects from Gamla have distinctively lower nickel content and some of them higher silver.

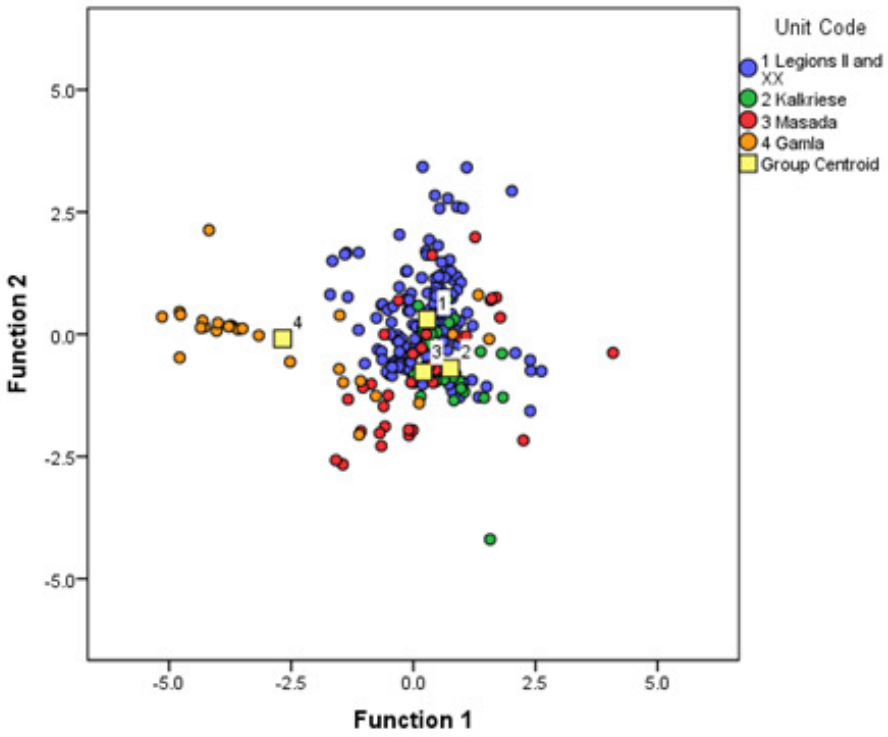

Figure 6.19 Discriminant scores plot of military objects from legions *II* and *XX*, Kalkriese, Masada and Gamla.

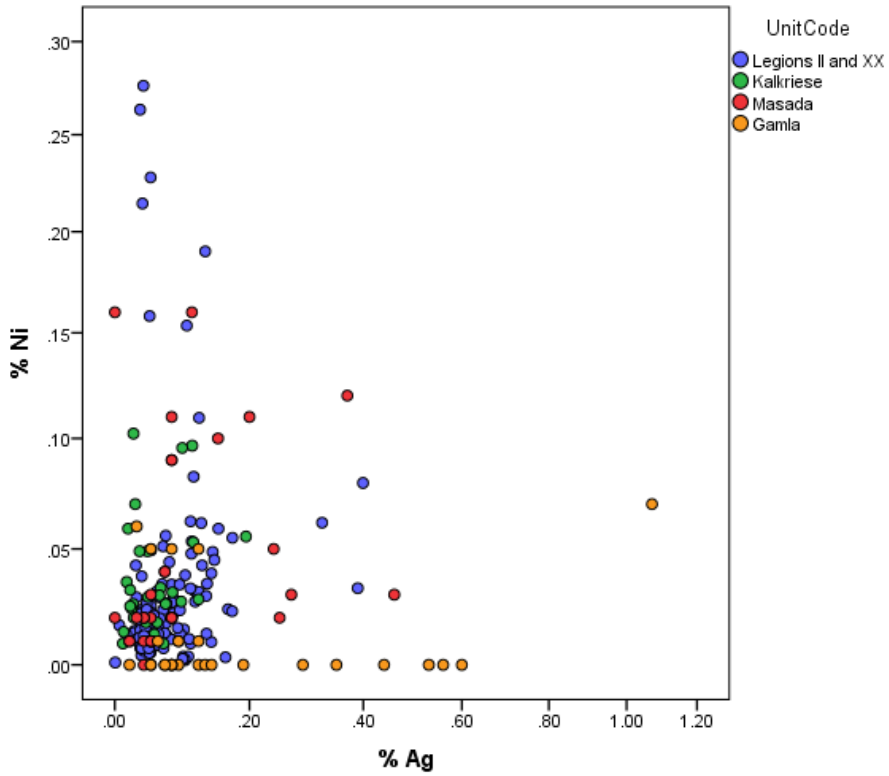

Figure 6.20 Bivariate plot of silver and nickel (rescaled to the copper) of objects from legion *II* and *XX* (considered together), Kalkriese, Masada and Gamla.

The military units involved at Gamla and Masada were diverse (Ponting 2012): whilst four legions took the town of Gamla (*X Fretensis, XV Apollinaris* and *V Macedonica*), the legion that lay siege to the fortress at Masada in AD70 was the *X Fretensis*, aided by auxiliary troops. A significant proportion of the material from Masada and some of the samples from Gamla however, show a significant overlap with equipment belonging to legions *II*, *XX* and the group from Kalkriese in terms of trace element composition. Since the small group of objects from Masada that differs in composition from the equipment of the British and German legions, does not contain any objects made of brass (or any significant level of zinc), it could mean that these objects were made in a different workshop to the bulk of the equipment, probably one that was local.

6.11 Legionary v. auxiliary equipment

Traditional scholarship suggests that the objects analysed were found on sites that are mostly associated with legionary units (see Section 2.2). However it is now understood that fortresses were rarely at full strength and could also have specific auxiliary units associated with them (Bishop 2012: 15). The overall result of the analysis does not show metallurgical differences

that could suggest the presence of different types of unit (except for the group of cavalry fittings from Carlisle). If equipment from auxiliary soldiers was included in these analyses, it does not seem to be different to that of the legionary units from a metallurgical point of view.

6.12 Difference between metal production and artefact production

A separation of the different metallurgical and manufacturing processes is necessary in constructing a model for the production of metal artefacts. There often seems to be an implied assumption in the literature that equates the place of metal production with the place (or even places) of object manufacture.

The metal could sometimes be smelted near the mines, as the copper cakes found near Trysglwyn Farm or the ingots from Amlwch, both at Parys Mountain on Anglesey, exemplify (Williams 1876: 108; Tylecote 1986: 23). The smelting of ores, however, required substantial amounts of timber to produce charcoal and even iron ores had to be transported sometimes if fuel was not available. The iron ore from Elba had to be taken to Papulonia (also in Elba) for smelting but then the blooms were transported to Pozzuoli, near Naples, where they were worked to finished products (Manning 1987: 594). In Faynan, Jordan, where large scale metal production was conducted, copper ores were brought to the site from across a very large region and not only from the nearest cluster of mines (Mattingly 2011: 180).

Ingots, once they were produced, could be transported and processed elsewhere (as the ingot from Sheepen and its inscription suggest). Brass, for example, seems to have been produced on the Continent, in areas that were already part of the Roman Empire (Bayley 1998) and then exported as ingots. The main source of the zinc in Roman brass has always been thought to be the Stolberg deposits near Aachen, in Germany (Craddock 1995) and there is evidence of large-scale production of cementation brass in Alesia and Lyon (Picon *et al* 1995; Desbet *et al* 2000).

Production of goods in the Roman world is generally regarded as the domain of a large number of small workshops rather than mass production from a few large production units (Manning 1987: 587). However, the production of Roman military equipment, at least in the first two centuries of the Empire, seems to have been a combination of private production and state control and/or production (see Section 2.6). The state could have controlled, or directly operated, the production of primary brass, which was then transported and processed in workshops, probably private, working for the army under contract. The specific gunmetal ranges identified could suggest that intermediate workshops operating within a regional recycling pool were controlling the mixing of brass and bronze to produce gunmetal for the army. For Olson (2013) large-scale production was

carried out in state-controlled facilities located in established provinces, that is it was region-dependent, rather than concentrated in a single manufacturing centre.

As was shown in Section 2.6, there is evidence for manufacturing and repair of equipment in forts and the civilian contexts around them. The army could acquire large quantities of equipment in a short period of time by relying on private manufacturers. This equipment could have then been given to soldiers and its cost gradually deducted from their pay (Herz 2011: 314). However, production of certain military items such as some *lorica segmentata* fittings or horse harness equipment (see Section 2.10.3.2) seem to have been manufactured by the state or at least with a high degree of centralisation. An analogous case is that of brooches, where specific military types such as the *Aucissa* form have similar compositions, independent of the place where they were found (Ponting & Segal 1998).

As seen in Section 2.10.3.2, Lyon (Lugdunum) was probably responsible for the production of large quantities of brass and could therefore have catered to the demands for primary brass throughout the western provinces. Lyon was a major centre for pottery and metal industries and had excellent communication with the rest of Gaul (Manning 1987: 597) and therefore easy access to ports and adjacent regions and provinces. The imperial mint at Lyon was established under Augustus and was the only mint issuing silver *denarii* from c.12BC to AD64 (Butcher & Ponting 2005: 164-5). Following the moving of bullion coin production to Rome by Nero in AD64, brass *dupondii* and *sestertii* were produced at Lyon and this continued under the Flavian emperors (Mattingly & Sydenham 1923: 58) and could have used the already existent brass production system used for military equipment production.

Other elements of the panoply such as scabbard fittings, belt plates or buckles, could have been locally produced in regional or in small local workshops. Veterans were also involved in the weapons business; one from Mainz describes himself as a *negotiator gladiarius*, or sword dealer (Herz 2011: 315).

As the specific gunmetal types suggest, workshops would carefully recycle alloys or existing fittings to fabricate new equipment. For instance, in one building at Carnuntum, scrap material was separated according to the alloy types (Bishop 1985a). Clearly, the army could still produce or recycle fittings and repair them in their *fabricae* as needed.

6.13 Methodological observation

Trace element analysis can also be used to differentiate between parts of a single object. As an example, the identification of the *lituus* fragments from Kalkriese as part of the same object could not necessarily have been achieved had only major elements been identified (see Section 5.9.3). In the case of an unleaded sheet of brass, for example, very similar (or nearly identical) zinc contents can be observed between apparently different objects.

6.14 Conclusion

In this chapter several aspects of Roman military metallurgy have been discussed. Alloy types are represented in proportions similar to other military contexts in Britain. Two general aspects of the assemblages analysed are in agreement with the general Roman metallurgical analysis literature: an inverse correlation between tin and zinc and an increase of leaded alloys over time (especially from the third century) indicating the mixing of brass with bronze. The analysis of gunmetal objects, which show groups of zinc-tin composition, suggests that care was exercised in producing these alloys. Colour and decoration seems to have been a fundamental quality of the equipment and the technological choices (alloy and plating) were aimed at enhancing the visual aspect.

The proportion of 'primary' brass is higher in sites associated with the army than in civilian contexts, strongly suggesting that the army controlled the production and distribution of the alloy. Comparative material from Israel and the large cementation crucibles from Gaul support the theory of centralised production of brass.

There is a strong suggestion of mechanization in the fabrication of sheet metal probably linked with the centralised production of brass. At least some of the fittings, such as those from *lorica segmentata* seem to have been centrally produced, as their composition and microstructure (particularly the grain size) suggest. Modes of production were also discussed: the manufacturing of some objects could have involved different places for the different stages in the production process: metal production, intermediate operations (such as sheet metal production) and final object manufacturing.

The objects analysed were compared with Iron Age military objects from the British pre-Roman Iron Age, these are almost always made of bronze and have higher levels of cobalt and nickel as trace elements. An explanation for the gradual change observed in trace element composition for

Roman military alloys was offered. This involves a complex recycling system accounting for the diffuse metallurgical patterns seen in equipment from legions *II* and *XX,* and which do not significantly change between the conquest period and the first half of the second century but are statistically different from those from Kalkriese. The difference could be explained by a large scale production of equipment in preparation for the conquest of Britain.

In the following chapter the conclusions of this thesis are brought together and proposals for the continuation of the project are outlined that could further support the theories discussed in this chapter.

Chapter 7: Conclusion

In Chapter 1 the research statement and the objectives of this study were established and the contents of the thesis were introduced. The objective was the chemical and metallographic characterisation of Roman military equipment in order to identify military units or workshops. Other aims discussed were to extend knowledge of production processes and modes of production and to investigate the importance of colour in military equipment. In Chapter 2 an overview was presented of the history of military equipment studies with its emphasis on typological studies and the relatively recent but still incipient scientific research on the subject. In Chapter 3 the methodology behind the selection of the assemblages and the analytical and statistical methods used for the analysis were explained. A brief history of the sites related to the objects analysed and the military units associated with them was presented in Chapter 4. The results of the analyses used for metallurgical characterisation were provided in Chapter 5 on a site-by-site basis first and then combined. In Chapter 6 the results were discussed in terms of the current understanding of the subject. This chapter presents the conclusions and the objectives achieved by this study and suggestions for future work.

7.1 Innovations in the metallurgical analysis of Roman military equipment

This thesis has combined different techniques of analysis to obtain a metallurgical characterization of the objects. As was shown in Chapter 2, scientific Roman military equipment studies have been limited in scope and combination of analysis techniques employed and this has resulted in scientific data that is very specific. This is probably the first study to combine both chemical and microstructural analysis of a significant number of examples of military equipment for a particular region of the Roman Empire. It is also the first attempt to identify military units by this combination of scientific techniques. As seen in the case of the *lorica segmentata* fittings discussed in Chapter 6, two independent methods of analysis (chemical analysis for zinc content and metallographic analysis to obtain grain size) were brought together to identify a group of fittings that was associated with a specific zinc content and grain size.

7.2 Limitations and Restrictions

The characterisation of the equipment in this thesis is not an attempt at a provenance study of the metal from which the objects were made, but a means to characterise the alloys used and to use these data to identify military units or workshops where the metal was used.

Geographically, the military equipment analysed is restricted to mainly south-western England (but also including objects from Chester and Carlisle) and one site from Germany, Kalkriese. Most of the objects date from the 1st century AD. However, some later objects from Chester, which date from the 3rd and 4th centuries AD, were also analysed to provide comparative material that shows differences in alloy type over time.

The sample size for the objects associated with *legio II Augusta* is relatively small, due to variability of reaction of curatorial staff to requests for access to material for analysis, but it was considered sufficient for the purpose of establishing a statistical similarity in terms of trace elements.

7.3 The results

An analysis of a total of 216 pieces of the legionary equipment panoply of the first century AD from Germany and mainly south-western England has shown that the objects from Germany are chemically different from those found in Britain. This difference is probably due to the British material being part of a large volume of equipment manufactured specifically in preparation for the conquest of Britain, or as part of the immediately previous German campaign. The German material on the other hand could have been circulating for a long period of time before the events at Kalkriese in AD9 consigned it to the archaeological record. The trace elements identified, nickel, antimony, silver and cobalt, are responsible for the difference between the two groups. If the latter possibility holds true, this could be some of the earliest Roman military equipment analysed.

No general differences between the equipment associated with legions *II Augusta* and *XX Valeria Victrix* was found through the metallurgical characterisation of copper-alloy military equipment (major, minor and trace element or metallographic analysis). However, it was possible to identify some local differences in the trace element pattern for legions *II* and *XX* at a site level. For example, higher arsenic and antimony levels were found in horse harness equipment from Carlisle, marking this out as a chemically distinct sub-group. Thus the trace element pattern of the British military copper-alloy 'recycling pool' changed slowly through internal recycling and the gradual incorporation of a relatively small input of fresh copper alloy with different trace element

characteristics, generating a diffuse trace element pattern with large ranges for nickel, antimony, cobalt and silver. This trace element pattern is however, statistically distinguishable from that of other recycling pools, such as that of the Lower Rhine area (see Chapter 6.8.5).

The production of metallic Roman military equipment has been considered by recent scholarship as the domain of small industries based around fortresses and fortress, from which the army obtained its entire supply (Bishop & Coulston 2006: 234). However, the archaeological evidence supporting this argument is directed to the repair of equipment or the fabrication of small objects such as belt buckles (Oldenstein 1974), but not necessarily the metal from which those objects are made.

Brass is an alloy associated with the Roman world and specifically with coinage and military equipment. The production of brass has been long thought by several scholars to have been controlled by the Roman state and there is archaeological evidence that suggests that this production was on a large scale (see Chapter 2.10.3.1 and 2.10.3.2).

The data from the analyses presented here suggest that the production of gunmetal for the manufacture of military fittings was also 'controlled' or at least regulated by the Roman state. As was discussed in Chapter 6.1.3, whilst gunmetal from civilian contexts shows broadly and randomly distributed zinc and tin contents (Dungworth 1995), the military objects analysed here showed specific compositional ranges. The compositional differences found suggest that the Roman army carefully controlled the mixing of brass and bronze objects to create gunmetal of specific compositional ranges.

The levels of zinc in brass, the specific ranges of zinc and tin in gunmetal, and the variety of plating methods, which include heat treatment post-application of tinning, for example, reflects that care was taken to achieve base-metal fittings that had a close resemblance to gold or silver. The choice of the copper alloys used in military equipment seems to have been predominantly motivated by the appearance of the metal.

In Chapter 2.6, the scale of production and the supply source of individual objects were discussed. This could have depended on specific circumstances, for example large scale during civil wars v. small local production (at a province level) during peacetime (Oldenstein 1985) or specific conditions such as proximity to already established production centres (as was the case in some areas of the Eastern Empire). In the first century AD the archaeological evidence suggests various production modes ranging from production of small fittings within and around forts (Oldenstein 1976) to large scale production of horse-harness fittings (Rabeisen 1990). The chemical composition

and microstructural analysis of some *lorica segmentata* fittings analysed for this thesis suggests that they were centrally produced, as they contain approximately 20% zinc and have an average grain size of 10µm. A small scale production system would produce a wider range of grain size for specific objects. In the case of these *lorica segmentata* fittings, however, a very specific composition and grain size was observed suggesting that the fittings were produced in a single workshop or in a limited number of workshops working to the same recipe under the administration of the State.

The ingot from Sheepen could represent an intermediate stage of a large scale brass production system starting with mass produced metal and ending with locally produced brass objects. This ingot shows morphological features that suggest that it was mechanically worked by rolling. The inscription on the ingot could be a mark of the maker or ownership or even some form of quality control, but in any case its presence in a workshop in Sheepen suggests a spatial division of the necessary processes to make brass objects; the metal could have been produced, mechanically worked and the objects made in different places.

7.4 Future work: some desiderata

The metallurgical characterisation presented in this thesis shows that British military equipment from the conquest period is different to that of the late Augustan from Kalkriese and Haltern in Germany. Whilst the sample size of the Kalkriese objects is statistically representative, it comprises mostly shield binding and metal sheet. Analysis of copper-alloy *lorica segmentata* fittings would be fundamental for comparison with the rest of the brass objects and to look for suggestions for mass production in earlier military equipment.

Analysis of material from more sites from along the Lower Rhine is needed to cover the period between Augustus and the conquest period and ideally extending the analysis into the second century in order to observe long-term metallurgical changes. Two sites would be the most suitable for the task: Neuss (Novaesium) and Xanten (Vetera I and II). *Legio XX Valeria Victrix* was garrisoned in Neuss from AD35 to 43 (Bishop 2013: 91) and analysis of military objects from the site (Simpson 2000) would be essential to understand military equipment production of the conquest and post-conquest periods. Vetera I was occupied by legions *V Alaudae* and *XXI Rapax* during its first timber phase from AD10-43 and legions *V Alaudae* and *XV Primigenia* once the fortress was rebuilt in stone from AD43 to 69 (Bishop 2012: 116). Analysis of objects from Vetera I would provide an excellent metallurgical characterisation of the alloys used on the Lower Rhine from the first

century AD, bridging the gap between the assemblages of Kalkriese and Haltern and the conquest of Britain.

The analysis of the data here shows that the metal used by *legio II Augusta* is very similar to that used by *legio XX Valeria Victrix*, the sample size being several times larger for *legio XX*. Whilst this imbalance is not likely to have a significant effect on the metallurgical similarities of the legions, equal sample sizes would provide greater statistical rigour in the case of the post-conquest period. Military equipment from Gloucester (Glevum) and Exeter (Isca Dumnoniorum) are likely to be the best for this task, since the legion is thought to have been divided between the two sites. Analysis of objects from Caerleon (Isca Augusta), the definitive base of *legio II,* would be key to study how the copper alloys of the legion changed with time and would also provide comparative material to *legio XX* at Chester (Deva), but negotiations to secure samples for this have thus far been in vain.

Analysis of objects from Colchester (Camulodunum), where *legio XX* established its first permanent base after arriving to Britain, would also be useful comparative material for the conquest period and could also provide equipment that belonged to veterans. In a later stage, analyses could include objects from British sites associated with legions other than *II* and *XX*, such as York (Eboracum) or military equipment of *legio II* from before the conquest of Britain (the legion came to Britain from Strasbourg [Argentoratum]). Analysis of metalwork from known auxiliary sites, such as Cirencester (Corinium) (Wacher & McWhirr 1982) could also show any differences that might exist between the metalwork used by legionaries and auxiliaries. Recent finds from other areas of the Empire, such as the 1st century AD copper-alloy armour fittings from León, associated with *legio VI* (Aurrecoechea 2010) could provide additional comparative material for the Tiberio-Claudian period.

For all the suggested analyses above, a sample size of between 30 and 50 objects for each site would be ideal. In this thesis, metallographic samples were taken from a third of the total number of objects analysed and this proportion is thought to be sufficient for the purposes of characterising the assemblages.

As discussed in Chapter 6, the places of production of metal, objects and intermediate stages in the process could differ. Analysis of unfinished and repaired equipment from structures that have been identified archaeologically as legionary workshops, such as those from Exeter (Bidwell 2007) or Hofheim (Ritterling 1904), or workshops associated with an auxiliary presence (such as Vindolanda) could also inform on the degree of recycling and/or centralisation in their production.

Additional cross-cultural analysis on the subject of military equipment in antiquity is needed, specifically the use of colour in the metallic panoply. The evidence needed, however (Gallic, Etruscan, Greek or Hellenistic, for example) is scarce. Tinning and silvering copper alloy seems to have been adopted from the Gauls and developed at Alesia (Bishop & Coulston 2006: 244). An Etruscan example that could inform on the use of colour or how it was perceived is provided by the 4th century BC Amazon Sarcophagus from Tarquinia. Here copper-alloy fittings (such as shoulder pieces and mounts), helmets and greaves are painted in yellow, showing a clear contrast to the white linen corselets of the soldiers (Gleba 2012: 49).

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APPENDIX 1: Photographs of the objects analysed

A1.1 South Cadbury Castle

Figure A1.1 CC113

Figure A1.2 CC136

Figure A1.3 CC145

Figure A1.4 CC147

Figure A1.5 CC148

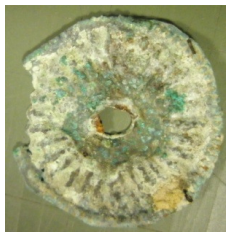

Figure A1.6 CC153

Figure A1.7 CC156

Figure A1.8 CC164

A1.2 Ham Hill

Figure A1.9 HamH1282_7

Figure A1.10 HamH_1290

Figure A1.11 HamH1291

Figure A1.12 HamH1292

Figure A1.13 HamH1324

Figure A1.14 HamH1912_75

Figure A1.15 HamH1994_8

Figure A1.16 HamH491994_34

Figure A1.17 HamH62_A_17

Figure A1.18 HamHA1193

Figure A1.19a HamHA1276

Figure A1.19b HamHA1276 SEM secondary electron composite image of *lorica* scales.

Figure A1.20 HamHA1286

Figure A1.21 HamHA1288

Figure A1.22 HamHA1314

Figure A1.23 HamHA1323a

Figure A1.24 HamHA1323b

Figure A1.25 HamHA1326

Figure A1.26 HamHB07

Figure A1.27 HamHE12

Figure A1.28 HamHE15

Figure A1.29 HamHE16

Figure A1.30 HamHE21

Figure A1.31 HamHE33

Figure A1.32 HamHF_11_1912_76

Figure A1.33 Gilded roundel from Ham Hill

A1.3 Carlisle

Figure A1.34 CSL 2042

Figure A1.35 CSL 2043

Figure A1.36 CSL 2788

Figure A1.37 CSL 3435

Figure A1.38 CSL 3897

Figure A1.39 CSL 3909

Figure A1.40 CSL 3946

Figure A1.41 CSL 3962

Figure A1.42 CSL 3985

Figure A1.43 CSL 4052

Figure A1.44 CSL 4380

Figure A1.45 CSL 4384

Figure A1.46 CSL 4387

Figure A1.47 CSL 4409

Figure A1.48 CSL 4413

Figure A1.49 CSL 4414

Figure A1.50 CSL 4450

Figure A1.51 CSL 4772

Figure A1.52 CSL 4781

Figure A1.53 CSL 4788

Figure A1.54 CSL 6043

Figure A1.55 CSL 6224

A1.4 Usk

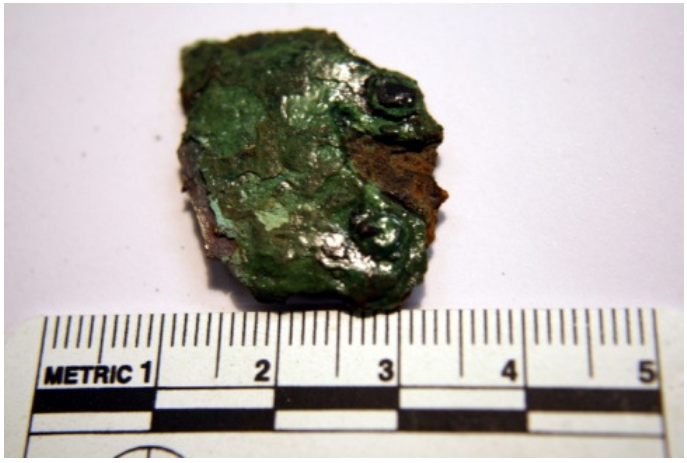

Figure A1.56 USK ManFig3No7

Figure A1.57 USK ManFig4No8

Figure A1.58 Usk ManFig5No36

Figure A1.59 USK ManFig8No6

Figure A1.60 USK ManP18No35

Figure A1.61 USK Man Pag40No3

Figure A1.62 USK ManPag40No8

A1.5 Chester

Figure A1.63 CHE3

Figure A1.64 CHE21

Figure A1.65 CHE57

Figure A1.66 CHE83a

Figure A1.67 CHE83b

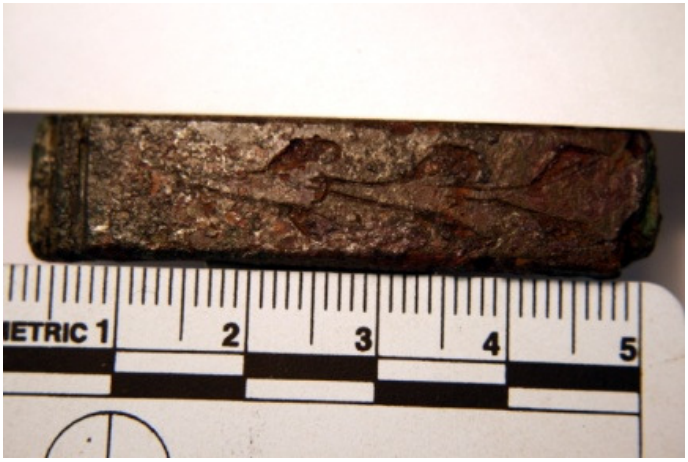

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Figure A1.69 CHE113

Figure A1.70 CHE142

Figure A1.71 CHE166

Figure A1.72 CHE177

Figure A1.73 CHE261

Figure A1.74 CHE349

Figure A1.75 CHE393

Figure A1.76 CHE424

Figure A1.77 CHE487

Figure A1.78 CHE614

Figure A1.79 CHE684

Figure A1.80 CHE701

Figure A1.81 CHE755

Figure A1.82 CHE785

Figure A1.83 CHE848

Figure A1.84 CHE992

Figure A1.85 CHE1124

Figure A1.86 CHE1174

Figure A1.87 CHE1180

Figure A1.88 CHE1181

Figure A1.89 CHE1272

Figure A1.90 CHE1513

Figure A1.91 CHE1516

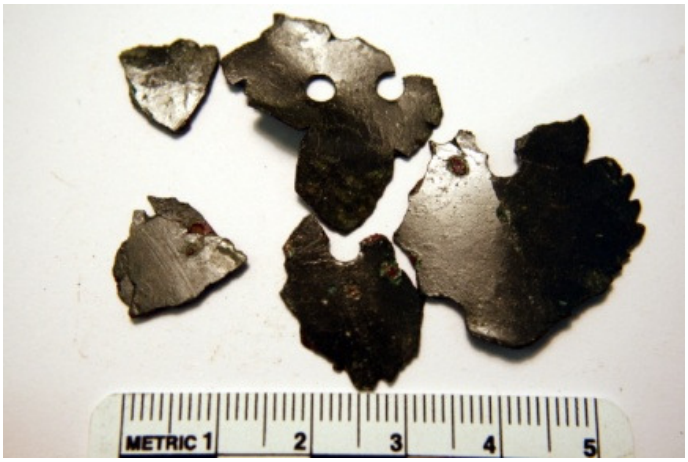
Figure A1.92 CHE1820

Figure A1.93 CHE1829

Figure A1.94 CHE1833

Figure A1.95 CHE1834

Figure A1.96 CHE1844



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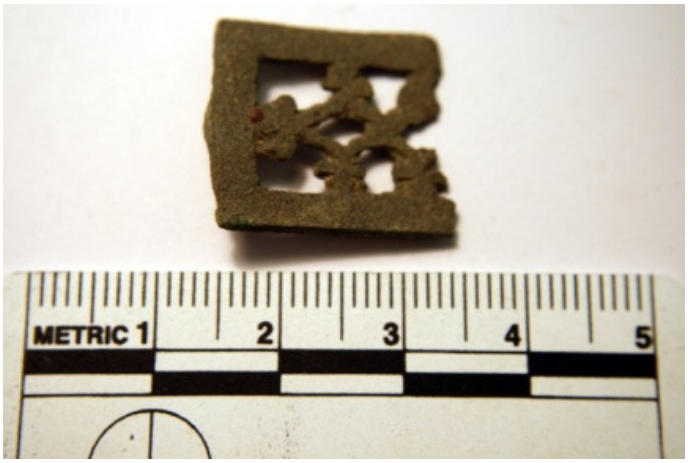

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Figure A1.99 CHE1920

Figure A1.100 CHE1945

Figure A1.101 CHE2024

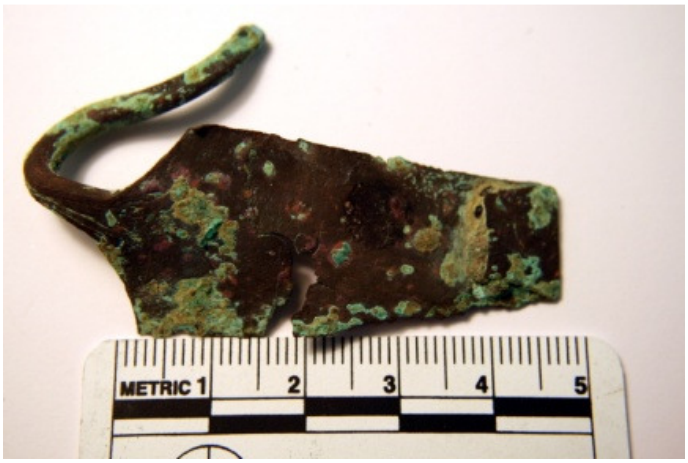

Figure A1.102 CHE2171

Figure A1.103 CHE2186

Figure A1.104 CHE2197

Figure A1.105 CHE2711

Figure A1.106 CHE8969

A1.6 Kingsholm

Figure A1.107 GLC48

Figure A1.108 GLC62

Figure A1.109 GLC121

Figure A1.110 GLC122

Figure A1.111 GLC125

Figure A1.112 GLC127

Figure A1.113 GLC128

Figure A1.114 GLC161

Figure A1.115 GLC192

Figure A1.116 GLC442

Figure A1.117 GLC505

Figure A1.118 GLC514

Figure A1.119 GLC538

Figure A1.120 GLC 813

Figure A1.121 GLC821

Figure A1.122 GLC822

Figure A1.123 GLC846

Figure A1.124 GLC852

Figure A1.125 GLC918

Figure A1.126 GLC964

Figure A1.127 GLC1046

Figure A1.128 GLC1085

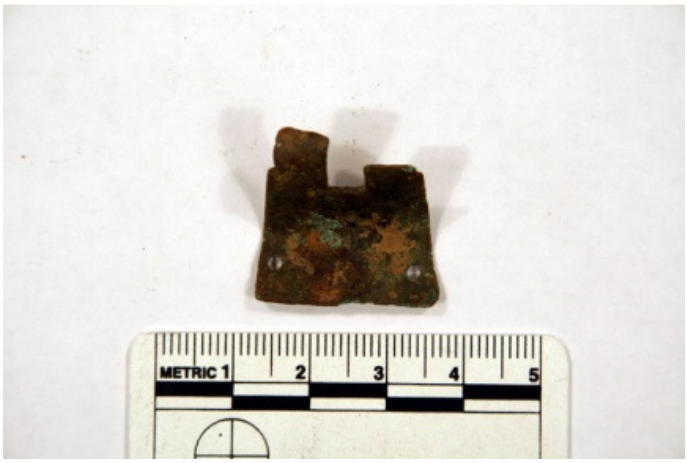

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Figure A1.130 GLC1139

Figure A1.131 GLC1176

Figure A1.132 GLC1199

Figure A1.133 GLC1206

Figure A1.134 GLC1234

Figure A1.135 GLC1298

Figure A1.136 GLC1308

Figure A1.137 GLC1309

Figure A1.138 GLC1315

Figure A1.139 GLC1324

Figure A1.140 GLC1347

Figure A1.141 GLC1349

Figure A1.142 GLC1376

Figure A1.143 GLC1446

Figure A1.144 GLC1457

Figure A1.145 GLC1489

Figure A1.146 GLC1533

Figure A1.147 GLC1550

Figure A1.148 GLC1573

Figure A1.149 GLC1611

Figure A1.150 GLC1683

Figure A1.151 GLC1685

Figure A1.152 GLC1921

Figure A1.153 GLC1989

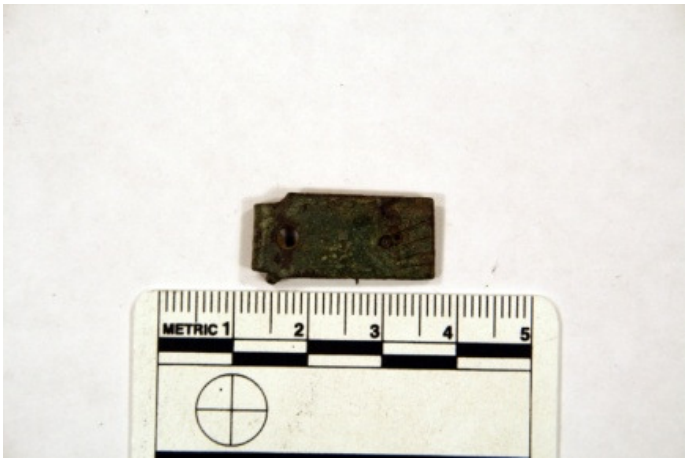

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Figure A1.158 GLC2153

Figure A1.159 GLC2160

Figure A1.160 GLC2161

Figure A1.161 GLC2167

Figure A1.162 GLC2275

Figure A1.163 GLC2290

Figure A1.164 GLC2312

Figure A1.165 GLC2337

Figure A1.166 GLC2356

Figure A1.167 GLC2357

Figure A1.168 GLC2359

Figure A1.169 GLC2360

Figure A1.170 GLC2361

Figure A1.171 GLC2362

Figure A1.172 GLC2378

Figure A1.173 GLC2439

Figure A1.174 GLC2602

Figure A1.175 GLC2677

Figure A1.176 GLC2680

Figure A1.177 GLC2693

Figure A1.178 GLC2741

Figure A1.179 GLC2759

Figure A1.180 GLC2857

Figure A1.181 GLC2866

Figure A1.182 GLC2933

Figure A1.183 GLC2935

Figure A1.184 GLC2936

Figure A1.185 GLC2943

A1.7 Kalkriese

Figure A1.186 K186

Figure A1.187 K742

Figure A1.188 K956

Figure A1.189 K2000

Figure A1.190 K2002

Figure A1.191 K2030

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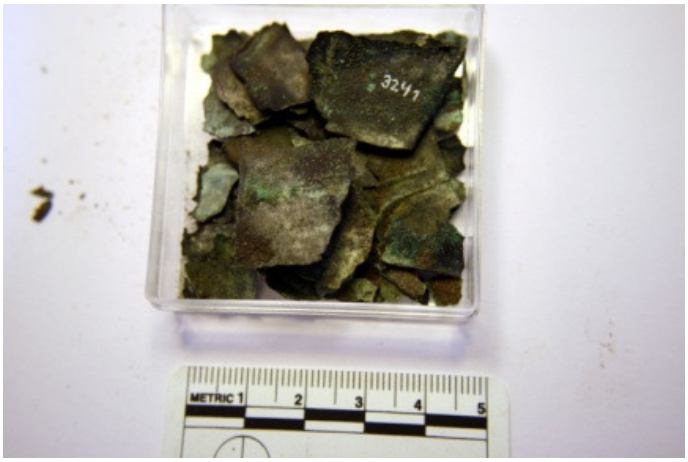

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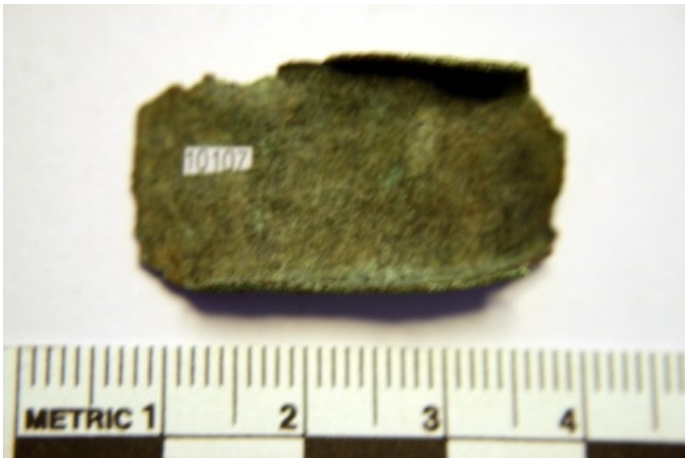

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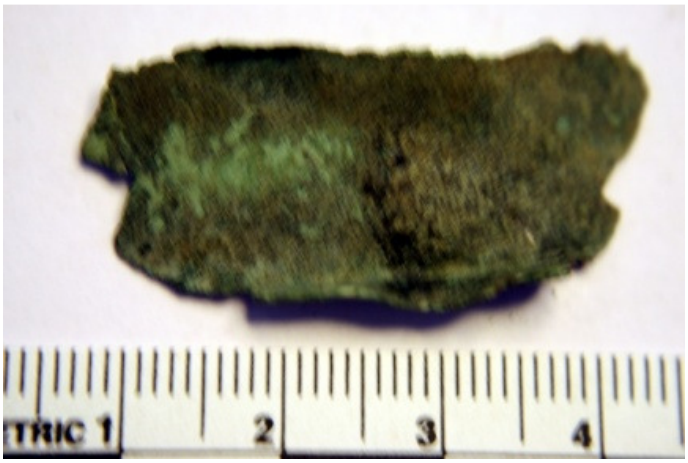

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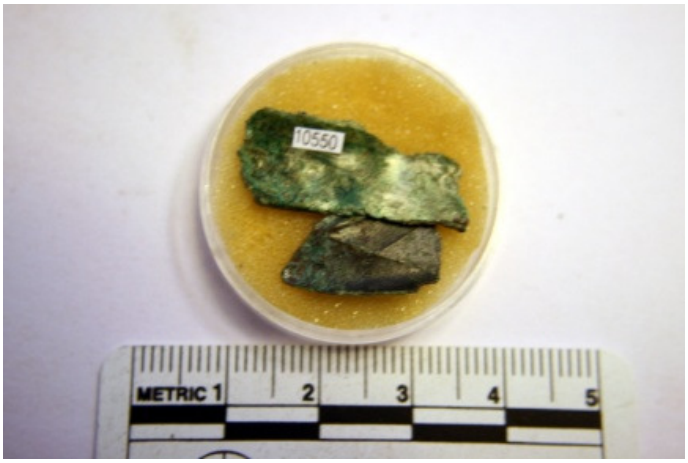

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Figure A1.209 K22373

Figure A1.210 K22622

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Figure A1.213 K26855

Figure A1.214 K28504

Figure A1.215 K33801

Figure A1.216 KProsp6_29/6/102

APPENDIX 2: AAS Data for all sites

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
CC113	Shield binding	77.2	<0.09	0.71	21.80	0.036	0.124	0.004	0.005	0.001	0.060	0.11	Brass
CC136	Lorica segmentata lobate Hinge	77.3	<0.30	<0.30	21.78	0.097	0.354	<0.007	<0.014	0.008	0.079	0.38	Brass
CC145	Lorica segmentata decorated roundel	81.2	<0.20	<0.19	17.50	0.100	0.394	<0.004	0.015	0.003	0.126	0.64	Brass
CC147	Lorica segmentata decorated roundel	78.1	<0.50	4.62	15.21	0.166	0.388	0.024	<0.023	0.013	0.394	1.11	Gunmetal
CC148	Lorica segmentata decorated roundel	75.7	<0.33	5.30	17.58	0.105	0.393	<0.007	0.023	0.008	0.221	0.64	Gunmetal
CC153	Lorica segmentata decorated roundel	78.6	0.83	2.56	17.03	0.099	0.372	<0.005	0.020	<0.002	0.103	0.42	Gunmetal
CC156	Belt dagger frog fragment	80.1	0.92	0.93	17.18	0.070	0.336	0.012	0.005	0.001	0.099	0.34	Brass
CC164	Horse Harness 3-way strap junction	88.9	2.00	7.440	0.008	0.115	0.022	0.027	0.651	0.008	0.079	0.38	Bronze

Table A2.1 Composition of Objects from South Cadbury (AAS).

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
USK ManFig3No7	*Lorica segmentata* lobate hinge	78.3	<0.10	<2.53	21.92	0.035	0.146	0.014	<0.02	<0.007	0.108	0.37	Brass
USK ManFig4No8	*Lorica segmentata* hinged buckle	74.7	<0.09	4.64	19.61	0.034	0.293	<0.012	<0.018	<0.006	0.133	0.96	Gunmetal
Usk ManFig5No36	Belt buckle	82.6	<0.099	<2.21	16.54	0.040	0.194	<0.012	<0.017	<0.006	0.084	0.33	Brass
USK ManFig8No6	Scabbard slide	52.9	32.91	9.26	1.13	0.064	3.067	<0.013	0.045	0.091	0.078	<0.07	Leaded Bronze
USK ManP18No35	Buckle tongue	78.1	12.43	8.32	0.23	0.050	0.180	0.049	0.469	0.007	0.077	0.14	Leaded Bronze
USK Man Pag40No3	Junction loop, Bishop's Type 1d	80.0	1.16	3.81	14.92	0.046	0.550	0.015	0.028	<0.007	0.129	<0.07	Gunmetal
USK ManPag40No8	Harness ring	83.4	2.95	12.32	0.28	0.044	0.447	<0.014	0.024	0.011	0.133	0.26	Leaded Bronze

Table A2.2 Composition of Objects from Usk (AAS).

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
HamH1282_7	Apron mount	64.1	9.80	0.98	24.88	0.074	0.105	0.012	<0.015	0.003	0.094	<0.18	Leaded Brass
HamH1290	Strap end fitting, Bishop Type 6a	77.6	<0.14	0.37	21.71	0.057	0.099	0.013	<0.007	0.002	0.036	0.10	Brass
HamH1291	Plate with part of a belt-hinge at one end	75.1	<1.64	<1.59	21.77	0.312	<0.169	0.052	0.212	0.042	0.544	1.99	Brass
HamH1292	Apron terminal	77.5	1.10	1.39	19.68	0.079	0.129	0.011	0.016	<0.002	0.114	<0.14	Brass
HamH1324	Horse harness pendant, Bishop Type 8g	80.9	2.70	6.16	8.88	0.114	1.109	0.032	<0.013	0.010	0.103	<0.16	Leaded Gunmetal
HamH1912_75	Stud	96.5	<0.36	2.40	<0.01	0.117	0.075	0.031	0.037	0.009	0.142	0.73	Bronze
HamH1994_8	Shield binding	84.9	0.54	13.03	0.72	0.124	0.055	0.062	0.006	0.001	0.435	0.10	Bronze
HamH49_1994_34	Junction loop	76.9	0.66	1.95	20.05	0.080	0.198	0.034	0.019	0.008	0.126	<0.19	Brass
HamH62_A_17	Junction loop	76.6	2.44	3.14	16.52	0.133	0.446	0.035	0.039	<0.003	0.185	0.47	Leaded Gunmetal
HamHA1193	Buckle	84.2	2.19	12.44	0.18	0.121	0.286	0.031	<0.014	<0.002	0.163	0.36	Leaded Bronze
HamHA1286	Mount	73.8	<0.73	1.33	24.26	0.140	0.341	0.039	<0.034	0.014	0.105	<0.43	Brass
HamHA1288	Apron plate	75.7	0.78	1.81	21.36	0.108	0.123	0.033	0.032	0.014	0.073	<0.29	Brass
HamHA1314	Harness circular boss	78.5	0.32	7.00	13.64	0.068	0.211	0.023	<0.008	0.003	0.052	0.18	Gunmetal
HamHA1323a	Female strap junction from horse harness	77.7	0.65	1.58	18.54	0.324	0.909	0.062	0.021	<0.001	0.073	0.15	Brass
HamHA1323b	Strap hook	76.6	0.86	1.43	20.83	0.072	0.078	0.018	0.017	<0.002	0.073	<0.18	Brass
HamHA1326	Female strap fastener, Type Bishop 1a	76.1	3.30	11.22	7.77	0.125	0.811	0.043	0.031	<0.003	0.142	0.51	Leaded Gunmetal
HamHB07	Stud	93.8	<0.67	5.08	<0.02	0.400	0.229	0.080	0.066	<0.005	0.370	<0.39	Bronze
HamHE12	Shield binding	75.6	<0.11	23.30	<0.01	0.162	0.368	0.003	0.006	0.003	0.355	0.23	Bronze
HamHE15	Horse harness fitting	76.0	3.35	6.57	11.63	0.142	1.486	0.049	0.035	0.007	0.189	0.58	Leaded Gunmetal
HamHE16	*Lorica segmentata* tie loop	76.0	0.34	1.19	22.24	0.065	0.090	0.009	<0.011	0.004	0.039	<0.13	Brass
HamHE21	Strap terminal	76.6	1.79	2.09	18.45	0.096	0.393	<0.005	0.020	0.006	0.034	0.50	Gunmetal
HamHE33	Shield binding	78.9	0.29	19.85	<0.01	0.113	0.478	0.082	<0.004	<0.001	0.129	0.12	Bronze
HamHF_11_1912_76	Stud	98.2	<0.23	1.14	<0.01	0.062	0.056	0.029	<0.011	0.008	0.136	0.38	Copper

Table A2.3 Composition of Objects from Ham Hill (AAS).

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
CSL 2042	End of strap junction	82.7	0.40	<3.016	16.21	0.045	0.286	0.019	<0.023	<0.008	0.189	0.38	Brass
CSL 2043	Strap junction	82.7	<0.12	<3.04	17.95	0.050	0.211	0.050	<0.024	0.014	<0.074	0.27	Brass
CSL 2788	Pendant, Bishop Type 11	76.2	3.18	8.05	11.59	0.092	0.331	0.023	0.042	<0.009	0.293	<0.09	Leaded Gunmetal
CSL 3435	Scale	83.4	<0.085	2.66	14.51	0.044	0.158	0.026	0.031	<0.006	0.051	<0.06	Gunmetal
CSL 3897	Strap end	69.7	17.21	11.29	0.34	0.086	0.122	0.026	0.029	0.008	0.155	0.64	Leaded Bronze
CSL 3909	Scales	82.7	<0.15	<3.84	17.68	0.052	0.233	0.022	0.055	0.011	0.099	<0.11	Brass
CSL 3946	*Lorica squamata*	91.7	0.20	<2.39	7.43	0.061	0.391	0.013	0.026	<0.007	0.073	<0.07	Brass
CSL 3962	Strap junction	78.3	<0.16	4.85	17.00	0.053	0.226	<0.021	0.045	<0.011	0.217	<0.11	Gunmetal
CSL 3985	Strap junction	75.8	<0.11	<2.69	22.77	0.037	0.149	<0.014	<0.021	<0.008	0.160	0.33	Brass
CSL 4052	Strap junction	80.3	<0.14	<3.4	18.03	0.108	0.324	<0.018	0.386	0.017	<0.083	0.17	Brass
CSL 4380	Ear or cheekpiece fragment	87.0	<0.09	2.46	10.76	0.048	0.155	0.015	0.027	<0.006	0.092	<0.06	Gunmetal
CSL 4384	*Lorica segmentata* hinge	79.9	0.42	<1.90	20.34	0.037	0.357	0.017	0.018	<0.005	0.073	<0.05	Brass
CSL 4387	*Lorica squamata*	83.3	<0.15	6.75	8.99	0.052	0.244	<0.02	<0.029	<0.011	<0.092	0.48	Gunmetal
CSL 4409	*Lorica segmentata* hook	88.2	0.29	5.82	5.58	0.035	0.222	0.015	0.018	0.015	<0.059	0.14	Gunmetal
CSL 4413	Ear protector	81.0	0.15	3.13	16.24	0.047	0.420	0.017	0.021	0.007	0.149	0.10	Gunmetal
CSL 4414	Lorica hinge fragment	78.7	0.18	<2.67	19.33	0.051	0.423	0.022	<0.021	<0.007	0.074	0.19	Brass
CSL 4450	*Lorica squamata*	77.6	0.09	<1.98	23.87	0.048	0.280	<0.01	<0.015	0.009	0.127	<0.05	Brass
CSL 4772	Saddle plate, Bishop (1988) type 6	75.4	0.22	2.98	21.55	0.036	0.191	<0.016	0.057	0.010	0.162	0.40	Gunmetal
CSL 4781	Mount	84.7	<0.12	<2.93	15.13	0.055	0.077	<0.016	0.024	0.009	0.198	0.32	Brass
CSL 4788	Cheek-piece binding	98.5	0.29	<2.63	<0.05	0.068	0.225	<0.014	<0.02	<0.007	0.100	0.51	Copper
CSL 6043	Pendant	81.8	<0.13	<3.30	17.93	0.059	0.413	0.032	<0.026	0.021	<0.081	<0.09	Brass
CSL 6224	Buckle plate	79.1	11.92	7.81	0.19	0.058	0.299	0.030	0.024	0.010	0.140	0.26	Leaded Bronze

Table A2.4 Composition of Objects from Carlisle (AAS).

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
CHE3	Horse harness pendant	68.7	11.98	8.19	10.21	0.083	0.487	0.042	<0.005	0.007	0.198	0.13	Leaded Gunmetal
CHE9	Newstead *lorica segmentata* loop fastener	75.2	8.05	3.06	12.98	0.047	0.535	0.021	0.011	0.012	0.118	<0.07	Leaded Gunmetal
CHE21	Fragment of dagger chape	81.6	0.10	1.50	16.29	0.039	0.295	0.012	<0.005	0.010	0.073	0.11	Brass
CHE57	Rectangular plate	74.9	15.11	9.10	0.09	0.072	0.336	0.039	0.009	0.010	0.154	0.21	Leaded Bronze
CHE83a	Newstead *lorica segmentata* loop fastener	76.6	13.35	9.60	0.03	0.055	0.165	0.033	0.006	0.013	0.123	<0.07	Leaded Bronze
CHE83b	Newstead *lorica segmentata* loop fastener	74.9	15.24	9.19	0.13	0.072	0.156	0.034	0.044	0.004	0.224	<0.07	Leaded Bronze
CHE89	Newstead *lorica segmentata* loop fastener	75.4	15.95	8.09	0.14	0.047	0.212	0.026	0.021	0.005	0.137	<0.07	Leaded Bronze
CHE108	Apron plate	85.6	6.73	0.79	6.50	0.106	0.168	0.011	<0.006	0.011	0.094	<0.07	Leaded brass
CHE113	Apron pendant	76.6	11.42	3.12	8.06	0.046	0.477	0.023	0.020	0.014	0.164	<0.07	Leaded Gunmetal
CHE142	*Lorica squamata*	85.5	0.55	6.29	6.91	0.046	0.397	0.023	<0.005	0.013	0.154	0.07	Gunmetal
CC156	Belt dagger frog fragment	80.1	0.92	0.93	17.18	0.070	0.336	0.012	<0.009	<0.002	0.099	0.34	Brass
CC164	Horse harness 3-way strap junction	88.9	2.00	7.44	<0.02	0.115	<0.044	0.027	0.651	<0.003	0.095	0.75	Bronze
CHE166	Belt plate fragment	70.1	16.90	11.79	0.23	0.141	0.558	0.014	0.034	0.009	0.189	<0.07	Leaded Bronze
CHE177	Scabbard runner	78.6	15.44	5.47	0.03	0.060	0.079	0.040	<0.005	0.011	0.154	0.12	Leaded bronze
CHE261	*Lorica squamata*	85.6	0.33	5.14	8.25	0.055	0.444	0.021	0.010	0.016	0.145	<0.07	Gunmetal
CHE349	Buckle (lorica segmentata?)	89.8	<0.04	1.33	8.62	0.056	0.070	0.004	<0.008	0.023	0.096	<0.1	Brass
CHE393	Newstead *lorica segmentata* loop fastener	77.6	10.28	7.00	4.58	0.055	0.230	0.019	<0.006	0.015	0.159	0.11	Leaded Gunmetal
CHE424	Newstead *lorica segmentata* loop fastener	82.4	9.24	7.92	0.08	0.036	0.068	0.020	0.009	0.011	0.124	0.09	Leaded Bronze
CHE487	Newstead *lorica segmentata* loop fastener	70.8	19.30	8.86	0.20	0.085	0.543	0.033	0.016	0.004	0.151	<0.08	Leaded Bronze
CHE614	Chain	85.2	0.19	<0.53	14.24	0.047	0.076	0.007	<0.005	0.011	0.084	0.16	Brass
CHE684	Newstead *lorica segmentata* loop fastener	72.9	11.71	7.51	7.25	0.096	0.378	0.016	0.009	0.002	0.166	<0.07	Leaded Gunmetal
CHE701	*Lorica segmentata* strap buckle	84.6	0.19	0.85	13.91	0.034	0.298	0.012	<0.006	0.013	0.086	<0.08	Brass
CHE755	*Lorica segmentata* lobate hinge	80.6	0.03	1.40	13.40	0.043	4.084	0.016	0.012	0.013	0.112	0.26	Brass
CHE785	Crest support	79.9	0.14	<0.54	19.52	0.051	0.113	0.018	0.193	0.015	0.080	<0.07	Brass
CHE848	*Lorica segmentata* tie hook	81.5	0.22	2.83	14.86	0.056	0.141	0.018	0.025	0.008	0.193	0.11	Gunmetal

Table A2.5 Composition of Objects from Chester (AAS). (Continues on next page).

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
CHE869	Chain	81.3	0.16	0.54	17.66	0.037	0.254	0.004	0.008	0.004	0.060	<0.06	Brass
CHE883	*Lorica segmentata* tie hook	85.6	0.30	2.71	10.58	0.047	0.392	0.027	0.012	0.011	0.180	0.12	Gunmetal
CHE1124	Copper alloy object	79.6	12.84	6.89	0.03	0.061	0.223	0.033	<0.005	0.011	0.127	0.18	Leaded Bronze
CHE1174	Newstead *lorica segmentata* loop fastener	70.3	18.14	7.64	3.04	0.078	0.475	0.032	0.015	0.012	0.138	0.08	Leaded bronze
CHE1180	*Lorica segmentata* girth hoop	72.2	14.63	9.60	2.17	0.077	0.913	0.044	0.010	0.005	0.184	0.17	Leaded Bronze
CHE1181	*Lorica segmentata* tie?	81.6	0.39	0.75	16.61	0.044	0.227	0.024	0.011	0.009	0.177	0.13	Brass
CHE1272	Copper alloy object	75.1	15.03	8.87	0.02	0.132	0.549	0.029	0.006	0.012	0.231	<0.06	Leaded Bronze
CHE1513	*Lorica segmentata* or strap attachment	80.4	0.06	<0.6	19.07	0.040	0.269	0.012	<0.006	0.014	0.125	<0.08	Brass
CHE1516	Belt plate fragment?	76.1	12.62	7.83	2.46	0.080	0.629	0.024	<0.004	0.005	0.142	0.13	Leaded Bronze
CHE1820	Belt plaque	75.4	13.81	9.95	0.12	0.071	0.447	0.027	0.019	<0.001	0.165	<0.06	Leaded Bronze
CHE1829	*Lorica segmentata* hinged buckle plate	83.9	1.07	1.96	12.49	0.040	0.175	0.019	0.006	0.008	0.176	0.18	Brass
CHE1833	Belt plate + 2 hooks	79.4	0.24	2.36	17.31	0.047	0.364	0.029	0.023	0.007	0.168	0.09	Gunmetal
CHE1834	*Lorica squamata*	83.8	0.10	2.37	13.06	0.059	0.363	0.016	0.010	0.011	0.175	<0.06	Gunmetal
CHE1844	Pendant	88.8	2.94	7.22	<0.01	0.070	0.269	0.014	0.172	0.016	0.203	0.32	Bronze
CHE1850	Pendant, leaf shaped	86.6	0.25	6.29	5.92	0.073	0.500	0.021	<0.004	0.004	0.205	0.14	Gunmetal
CHE1855	Belt-plate fragment	71.0	18.79	7.70	1.86	0.054	0.359	0.021	0.033	0.009	0.186	<0.09	Leaded Bronze
CHE1920	Belt plate with loop	79.7	5.06	14.31	0.10	0.075	0.109	0.016	<0.0063	0.018	0.400	0.17	Leaded bronze
CHE1945	*Lorica segmentata* hook	86.5	0.25	1.90	10.43	0.063	0.212	0.020	0.023	0.020	0.237	0.36	Brass
CHE2024	Belt plate	72.3	16.90	10.36	0.07	0.055	0.074	0.025	<0.005	0.009	0.154	<0.06	Leaded Bronze
CHE2171	Pendant	85.1	<0.03	1.74	12.50	0.058	0.330	0.019	0.012	0.016	0.204	<0.08	Brass
CHE2186	Newstead *lorica segmentata* loop fastener	71.2	20.55	7.67	0.06	0.058	0.261	0.034	0.006	0.009	0.164	<0.07	Leaded Bronze
CHE2197	Newstead *lorica segmentata* loop fastener	76.6	16.01	6.38	0.16	0.049	0.415	0.020	0.040	0.013	0.160	0.12	Leaded Bronze
CHE2711	Pendant	81.9	0.82	3.01	14.05	0.072	<0.013	0.026	0.011	0.013	0.130	<0.08	Gunmetal
CHE8765	*Lorica squamata*	83.9	0.12	2.55	12.74	0.058	0.314	0.017	0.011	0.002	0.239	<0.1	Gunmetal
CHE8969	Harness strap distributor	74.0	17.89	7.53	0.01	0.101	0.059	0.028	<0.005	0.011	0.117	0.27	Leaded Bronze
CHE992	Newstead *lorica segmentata* loop fastener	67.9	24.10	7.16	0.18	0.055	0.229	0.019	0.025	0.005	0.255	0.07	Leaded Bronze

Table A2.5 (continued). Composition of Objects from Chester (AAS).

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
GLC48	Rosette	74.7	2.05	0.12	20.18	0.107	0.168	0.052	<0.005	<0.001	0.034	<0.05	Leaded Brass
GLC62	Corbridge *lorica segmentata* hinged plate	78.9	0.24	0.30	17.93	0.057	0.562	0.012	<0.005	<0.002	0.084	<0.13	Brass
GLC121	Horse harness junction loop	78.9	2.08	1.76	9.33	0.091	0.600	0.014	0.004	<0.002	0.061	<0.11	Leaded Gunmetal
GLC122	Horse harness mount	70.8	11.05	3.38	5.70	0.130	1.849	0.009	0.052	0.019	0.063	0.15	Leaded Gunmetal
GLC125	Buckle, plated	73.7	16.94	8.24	1.43	0.067	0.538	0.035	<0.005	<0.001	0.226	0.08	Leaded Bronze
GLC127	Belt plate	78.8	0.15	0.31	20.82	0.032	0.201	0.015	0.008	0.004	0.032	<0.11	Brass
GLC128	Corbridge *lorica segmentata* hinged plate fragment	79.9	0.13	<0.09	20.38	0.050	0.316	0.010	<0.003	0.004	0.059	<0.01	Brass
GLC161	Newstead *lorica segmentata*?	82.7	0.08	0.14	17.85	0.006	0.120	0.017	<0.005	0.003	<0.011	0.08	Brass
GLC192	Kalkriese *lorica segmentata* hinge?	83.6	0.77	<0.12	19.84	0.040	0.266	0.225	0.007	<0.003	0.066	0.16	Brass
GLC442	Catch plate pendant fragment?	54.9	1.99	0.97	16.11	0.098	0.715	0.143	<0.006	<0.001	0.189	0.07	Leaded Brass
GLC505	Riveted plate fragment (possibly tie loop from helmet)	76.3	0.07	0.20	19.99	0.055	0.116	0.011	0.004	0.005	0.040	<0.11	Brass
GLC514	Rectangular plate	88.0	2.04	2.82	10.10	0.114	0.515	0.050	0.007	0.004	0.312	0.45	Gunmetal
GLC538	Gilt harness fitting	98.1	0.74	<0.11	<0.03	0.173	0.105	0.055	<0.005	0.003	0.381	0.62	Copper
GLC813	Harness fitting, baldric?/horse harness	88.6	0.42	4.00	0.45	0.045	0.411	0.006	0.008	<0.002	0.041	0.14	Bronze
GLC821	Corbridge *lorica segmentata*	86.2	1.82	3.74	5.31	0.148	0.157	0.058	0.009	0.005	0.373	0.46	Gunmetal
GLC822	Horse harness spectacle strap fastener	73.9	2.81	2.29	6.61	0.051	0.499	0.010	0.002	0.002	0.103	<0.06	Leaded Gunmetal
GLC846	Shield binding	79.0	<0.039	0.31	17.67	0.026	0.086	0.014	<0.005	<0.001	0.066	<0.05	Brass
GLC852	Horse harness junction loop, Bishop Type 8	99.1	0.60	0.17	<0.02	0.029	0.075	0.043	<0.006	<0.001	0.139	0.34	Copper
GLC918	Horse harness junction loop, Bishop Type 3g	80.7	0.97	1.84	17.52	0.047	0.357	0.016	0.018	<0.001	0.067	<0.11	Gunmetal
GLC964	Corbridge *lorica segmentata* lobate hinge	80.1	0.41	0.97	15.59	0.047	0.551	0.016	<0.004	0.003	0.109	<0.05	Brass
GLC1046	Corbridge *lorica segmentata* fitting	78.6	0.71	0.70	18.50	0.045	0.267	0.012	0.058	<0.002	0.064	<0.12	Brass
GLC1085	Corbridge *lorica segmentata* lobate hinge	70.2	0.08	1.06	16.91	0.023	0.187	0.012	0.016	<0.001	0.162	0.09	Brass
GLC1099	Kalkriese *lorica segmentata* hinged fitting	88.5	1.04	4.60	3.01	0.066	0.150	0.050	0.017	0.002	0.269	0.12	Bronze
GLC1139	Corbridge *lorica segmentata* hook fastener	75.5	0.08	0.18	22.94	0.047	0.117	0.009	0.011	0.003	0.039	0.12	Brass

Table A2.6 Composition of Objects from Kingsholm (AAS) (continues on next page).

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
GLC1176	Horse Harness Junction loop	82.9	2.21	3.44	10.75	0.083	0.916	0.022	0.006	<0.003	0.081	0.12	Leaded Gunmetal
GLC1199	Corbridge *lorica segmentata* hinged plate	91.6	1.39	3.75	4.50	0.111	0.352	0.064	0.014	0.007	0.444	0.59	Gunmetal
GLC1206	Plated horse harness mount	79.1	0.08	<0.12	18.08	0.093	2.492	0.013	0.209	0.011	0.033	<0.07	Brass
GLC1234	Buckle plate	73.3	<0.048	0.14	22.14	0.037	0.137	0.013	0.010	0.009	0.081	0.28	Brass
GLC1298	Corbridge *lorica segmentata* hinged plate	78.9	0.63	1.00	16.84	0.047	0.656	0.010	<0.004	0.002	0.050	<0.11	Brass
GLC1308	Horse harness wolf's head terminal	77.5	0.26	1.39	19.29	0.038	0.253	0.015	0.008	0.003	0.043	0.18	Brass
GLC1309	Horse harness attachment for wolf head pendant	97.1	<0.058	0.15	<0.02	0.044	0.007	0.021	0.015	0.002	0.073	0.30	Copper
GLC1315	Decorated strip, scabbard	88.8	0.11	<0.09	12.80	0.036	0.196	0.011	0.007	0.002	0.032	<0.05	Brass
GLC1324	Cone shaped ferule	81.6	2.39	4.49	6.84	0.117	0.520	0.106	<0.004	<0.002	0.390	0.29	Leaded Gunmetal
GLC1347	*lorica segmentata* fitting?	91.8	0.44	3.89	4.78	0.147	0.239	0.046	0.022	<0.002	0.365	0.22	Gunmetal
GLC1349	Horse harness *phalera*	73.9	<0.059	<0.08	20.79	0.038	0.362	0.010	0.006	0.006	0.104	<0.09	Brass
GLC1376	Hinged plate	80.0	0.07	3.42	11.17	0.046	0.362	0.151	0.009	<0.002	0.016	0.24	Gunmetal
GLC1446	Strap fastener (female)	76.9	4.99	2.53	10.07	0.085	0.775	0.015	0.043	<0.002	0.076	0.23	Leaded Gunmetal
GLC1457	Button and loop fastener? - Pendant fragment?	83.8	16.22	0.64	0.32	0.040	0.049	0.022	<0.005	<0.002	0.217	<0.06	Leaded Copper
GLC1489	Rectangular plate	64.8	1.25	1.75	17.58	0.034	0.529	0.238	0.006	<0.001	0.056	<0.06	Gunmetal
GLC1533	Corbridge *lorica segmentata* hinged plate	76.6	0.09	<0.08	20.53	0.034	0.129	0.007	<0.003	0.002	0.038	<0.01	Brass
GLC1550	Corbridge *lorica segmentata* fastener	98.2	0.51	<0.01	0.09	0.082	0.006	0.028	<0.004	<0.002	0.198	0.24	Copper
GLC1573	Belt plate?	74.6	0.09	0.37	21.46	0.048	0.125	0.005	<0.003	0.004	0.041	<0.01	Brass
GLC1611	Horse harness strap loop (spectacled)	80.1	0.64	1.04	16.86	0.039	0.190	0.013	0.004	0.002	0.111	<0.05	Brass
GLC1683	Scabbard chape	87.0	0.06	8.47	0.03	0.069	0.172	0.054	<0.005	0.002	0.472	0.38	Bronze
GLC1685	Strip, from a scabbard	79.9	0.70	0.47	17.96	0.045	0.360	0.010	<0.003	0.002	0.046	0.10	Brass
GLC1921	Corbridge *lorica segmentata* hinged plate fragment	76.0	0.45	0.16	19.41	0.166	0.146	0.022	0.004	0.002	0.035	<0.05	Brass
GLC1989	Corbridge *lorica segmentata* hinged plate	72.0	1.14	<0.1	24.95	0.049	0.204	0.225	0.008	0.007	0.046	0.17	Brass
GLC2105	Corbridge *lorica segmentata* fitting?	83.8	2.23	4.64	4.38	0.088	0.233	0.033	0.008	0.002	0.245	0.30	Leaded Gunmetal

Table A2.6 (continued). Composition of Objects from Kingsholm (AAS) (continues on next page).

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
GLC2136	Binding with punched hole	97.4	0.07	0.21	0.08	0.059	0.171	0.016	<0.005	<0.001	0.040	<0.12	Copper
GLC2147	*lorica segmentata* buckle and plate fragment	80.3	0.14	0.36	18.24	0.015	0.188	0.013	0.008	0.005	0.030	<0.06	Brass
GLC2148	*lorica segmentata* hinged fitting	83.9	0.91	0.40	18.21	0.057	0.334	0.012	<0.006	<0.003	0.114	<0.07	Brass
GLC2153	Horse harness crescent shaped mount	80.3	3.22	2.46	0.30	<0.001	0.252	<0.002	<0.005	<0.001	0.186	<0.05	Leaded Bronze
GLC2160	Horse harness junction loop	85.4	0.51	3.30	10.17	0.050	0.143	0.025	<0.006	<0.001	0.127	<0.07	Gunmetal
GLC2161	Horse harness pendant, Bishop Type 7	78.2	0.07	0.18	18.79	0.043	0.104	0.007	0.004	<0.0015	0.055	<0.1	Brass
GLC2167	Pendant? Strap end?	95.0	0.38	4.24	1.14	0.039	0.446	0.024	<0.006	0.004	0.053	<0.07	Bronze
GLC2275	Riveted plate fragment	87.1	0.30	3.22	5.57	0.100	0.087	0.150	<0.005	0.001	0.016	1.21	Gunmetal
GLC2290	Binding	82.9	1.19	0.49	15.25	0.035	0.252	0.265	<0.005	0.003	0.053	0.20	Brass
GLC2312	Corbridge *lorica segmentata* buckle plate	78.2	0.54	0.24	14.18	0.044	0.548	0.010	<0.004	<0.0015	0.058	0.11	Brass
GLC2337	Horse harness triangular strap loop, Bishop Type 7	79.7	0.05	<0.11	5.65	0.039	0.093	0.010	0.204	0.006	0.043	0.09	Brass
GLC2356	Strip, from a scabbard	89.7	0.13	0.25	6.53	0.048	0.422	0.012	<0.005	0.003	0.039	<0.11	Brass
GLC2357	Strip	78.9	0.92	2.16	17.31	0.050	0.309	0.016	<0.004	<0.001	0.148	0.05	Brass
GLC2359	Hinged plate (traces of plating)	75.6	0.08	0.12	21.26	0.038	0.302	0.011	0.006	0.002	0.033	<0.05	Brass
GLC2360	Horse harness junction loop Type 1, fragment	79.2	2.39	2.78	14.55	0.043	0.455	0.020	0.012	<0.001	0.155	0.15	Leaded Gunmetal
GLC2361	Horse harness junction loop/fastener	75.6	0.31	2.64	13.32	0.050	0.330	0.017	0.013	0.002	0.094	0.20	Gunmetal
GLC2362	Horse harness junction loop fragment	74.2	0.46	0.88	20.79	0.045	0.293	0.014	<0.004	<0.001	0.071	0.14	Brass
GLC2378	Corbridge *lorica segmentata* hinged plate	83.6	0.07	0.14	18.76	0.040	0.313	0.023	0.008	0.003	0.059	0.14	Brass
GLC2439	Corbridge *lorica segmentata* hinged strap fitting	88.1	0.22	2.81	4.24	0.096	0.149	0.037	<0.004	0.002	0.137	0.25	Gunmetal
GLC2602	Binding	78.4	0.15	0.37	20.29	0.052	0.119	0.012	<0.004	0.002	0.049	0.13	Brass
GLC2677	Horse harness strap terminal	90.5	0.09	0.59	12.20	0.046	0.249	0.010	<0.004	0.004	0.078	<0.05	Brass
GLC2680	Binding	75.1	0.63	<0.09	21.96	0.130	0.498	0.013	0.015	0.005	0.020	<0.10	Brass
GLC2693	Horse harness spectacle harness mount	83.2	1.07	0.84	13.82	0.037	0.948	0.038	<0.006	0.003	0.040	<0.07	Brass
GLC2741	Strip, folded	88.4	1.27	5.51	1.87	0.078	0.108	0.026	0.007	0.002	0.171	<0.11	Bronze

Table A2.6 (continued). Composition of Objects from Kingsholm (AAS) (continues on next page).

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
GLC2759	Corbridge *lorica segmentata* loop fastener	75.9	0.42	1.55	17.94	0.035	0.443	0.021	<0.005	0.001	0.038	<0.05	Brass
GLC2857	Pendant/strap end	77.7	0.06	0.42	22.58	0.041	0.128	0.015	0.016	0.005	0.093	0.31	Brass
GLC2866	Rectangular plate	99.0	0.32	0.11	<0.02	0.392	0.071	0.033	<0.006	<0.001	0.197	0.46	Copper
GLC2933	Bishop Type I horse harness trifid pendant	79.9	1.11	0.25	16.49	0.051	0.155	0.016	<0.007	0.003	0.061	0.26	Brass
GLC2935	Corbridge *lorica segmentata* hook fastener	79.8	0.07	0.15	16.76	0.029	0.208	0.028	0.006	0.006	0.113	<0.07	Brass
GLC2936	Rectangular plate	77.2	0.07	0.09	17.85	0.036	0.183	0.012	<0.005	0.002	0.044	<0.05	Brass
GLC2943	Dagger frog?	99.7	0.06	<0.09	<0.02	0.031	0.030	0.011	0.006	<0.002	0.051	0.09	Copper

Table A2.6 (continued). Composition of Objects from Kingsholm (AAS).

Sample	Description	% Cu	% Pb	% Sn	% Zn	% Ag	% Fe	% Ni	% Co	% Mn	% Sb	% As	Alloy Type
K186	Sheet fragment	99.0	0.40	<0.092	<0.015	0.110	0.006	0.097	<0.004	<0.0016	0.110	0.27	Copper
K742	Shield binding	78.5	0.18	0.15	20.54	0.059	0.153	0.018	0.006	0.009	0.037	0.31	Brass
K956	Shield binding	76.9	0.90	0.83	21.09	0.081	0.167	0.031	0.007	<0.001	0.024	<0.049	Brass
K2000	Shield binding	79.2	0.19	0.52	19.85	0.018	0.119	0.059	0.007	0.003	<0.013	0.08	Brass
K2002	Shield binding	77.4	0.09	0.32	21.90	0.094	0.183	0.027	<0.004	0.001	0.022	<0.047	Brass
K2030	Lituus fragment	79.8	0.11	0.40	19.05	0.071	0.165	0.026	0.005	0.001	0.220	0.16	Brass
K3223	Shield binding	77.7	0.08	0.34	21.69	0.025	0.136	0.026	<0.005	0.004	<0.013	<0.062	Brass
K3241	Shield binding	79.2	0.06	0.32	20.25	0.023	0.131	0.024	<0.005	0.003	0.031	<0.049	Brass
K3797	Shield binding	76.6	0.23	0.17	22.73	0.068	0.180	0.009	0.005	0.008	0.039	<0.098	Brass
K5610	Belt buckle	86.1	2.63	7.10	2.96	0.096	0.665	0.096	<0.005	<0.002	0.150	0.21	Leaded Bronze
K7094	Shield binding	77.8	0.05	0.42	21.29	0.045	0.113	0.049	<0.005	0.003	0.091	0.16	Brass
K9847	Shield binding	80.8	0.12	0.63	18.18	0.021	0.252	0.025	<0.005	0.003	0.022	<0.056	Brass
K9900	Lituus fragment	78.7	0.12	0.51	19.98	0.055	0.329	0.013	0.011	<0.001	0.042	0.21	Brass
K10282-10107-10412-10413	Lituus	79.6	0.43	0.37	19.55	0.026	0.093	0.102	<0.005	<0.003	0.045	<0.06	Brass
K10550	Shield binding	76.2	0.22	0.27	23.01	0.120	0.137	0.028	0.007	<0.0014	0.048	<0.092	Brass
K10597	Lituus	76.5	0.34	0.60	22.33	0.028	0.100	0.070	<0.004	<0.0015	0.038	<0.098	Brass
K11816	Shield binding	77.9	0.06	0.31	21.55	0.026	0.168	0.020	<0.004	0.001	<0.01	<0.046	Brass
K1318143-S6	Helmet crest holder	97.0	2.60	0.28	<0.024	0.016	0.045	0.036	0.007	0.003	<0.012	<0.061	Leaded Copper
K13695/E	Shield binding	77.8	0.09	0.47	21.09	0.112	0.138	0.053	0.012	0.017	0.045	0.18	Brass
K21543	Lituus fragment	79.3	0.07	0.42	19.66	0.034	0.438	0.049	<0.004	0.008	0.033	<0.105	Brass
K22373	Helmet knob	71.2	22.41	5.56	0.04	0.194	0.169	0.056	0.018	<0.001	0.133	0.18	Leaded Bronze
K22622	Shield binding	78.8	0.14	<0.107	20.67	0.064	0.111	0.033	0.010	0.002	0.054	0.13	Brass
K25925	Shield binding	77.3	0.05	0.24	22.14	0.043	0.180	0.018	0.006	0.003	0.062	<0.102	Brass
K26305	Shield binding	79.0	0.13	0.17	20.58	0.021	0.093	0.032	<0.004	0.003	0.032	<0.046	Brass
K26855	Shield binding	79.2	0.06	0.09	20.45	0.012	0.141	0.014	<0.004	<0.001	<0.011	<0.048	Brass
K28504	Socket	79.3	0.07	0.17	20.24	0.046	0.090	0.029	<0.004	<0.001	0.032	<0.047	Brass
K33801	Sheet fragment	85.6	<0.023	14.21	<0.025	0.011	0.122	0.009	<0.005	<0.003	0.018	<0.063	Bronze
KProsp6_29/6/102	Shield binding	99.3	<0.061	0.13	0.03	0.062	0.015	0.030	<0.003	<0.0015	0.173	0.29	Copper

Table A2.7 Composition of Objects from Kalkriese (AAS).

APPENDIX 3: Optical Metallography Micrographs

A3.1 South Cadbury Castle

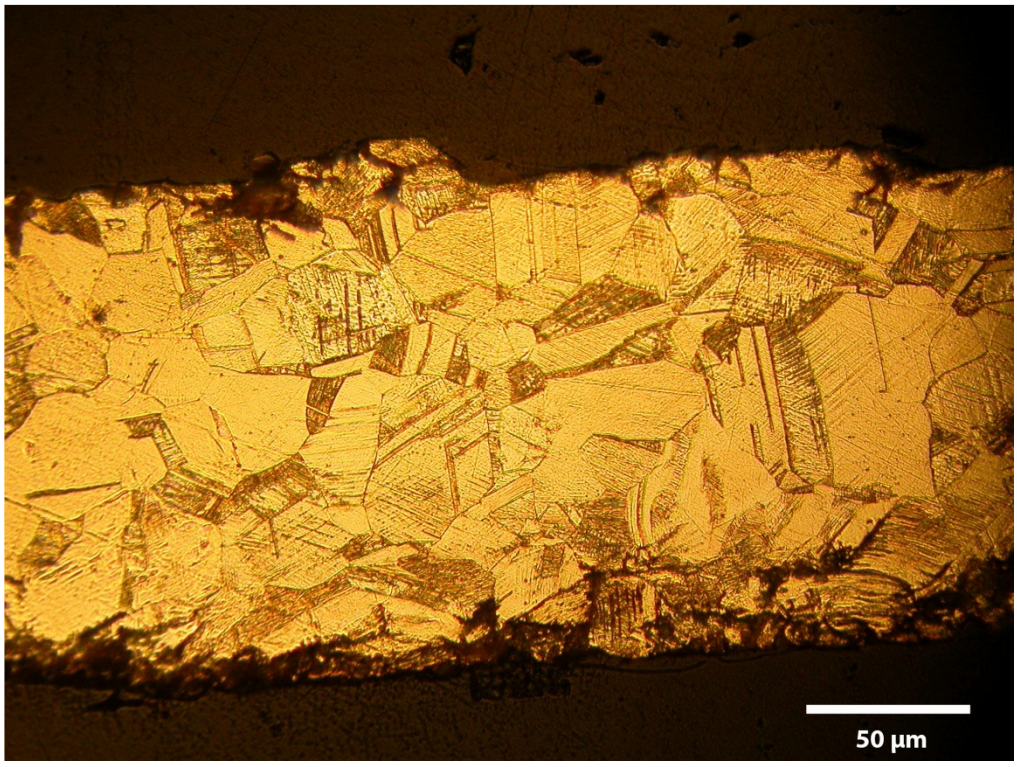


Figure A3.1 CC113

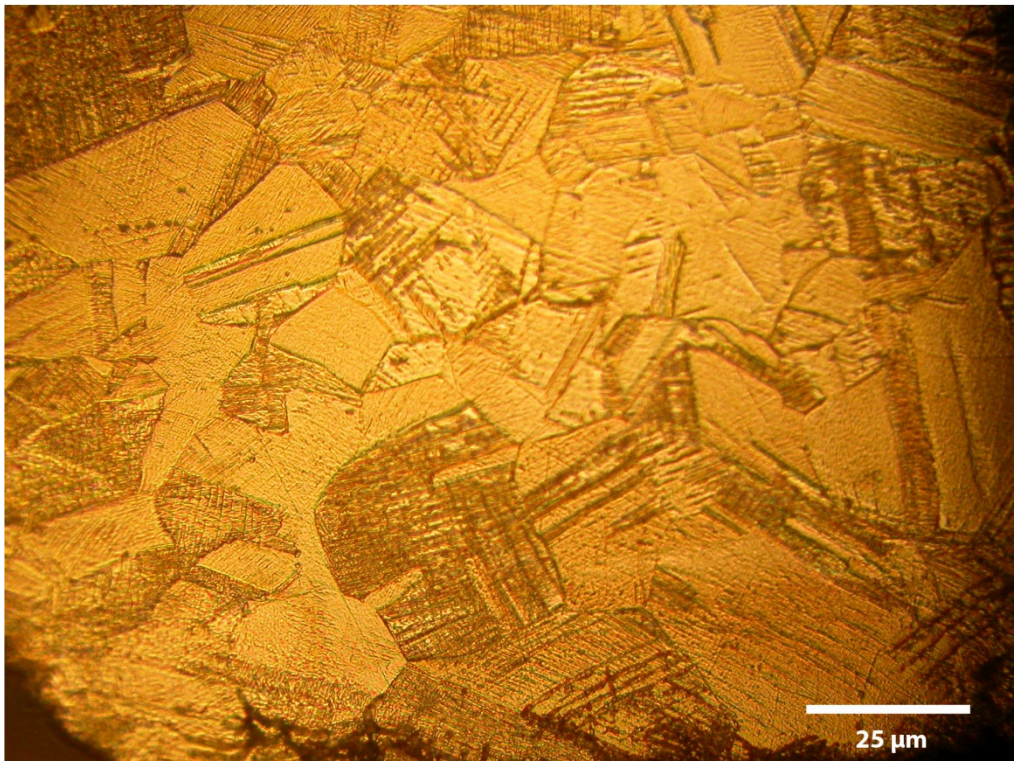


Figure A3.2 CC113

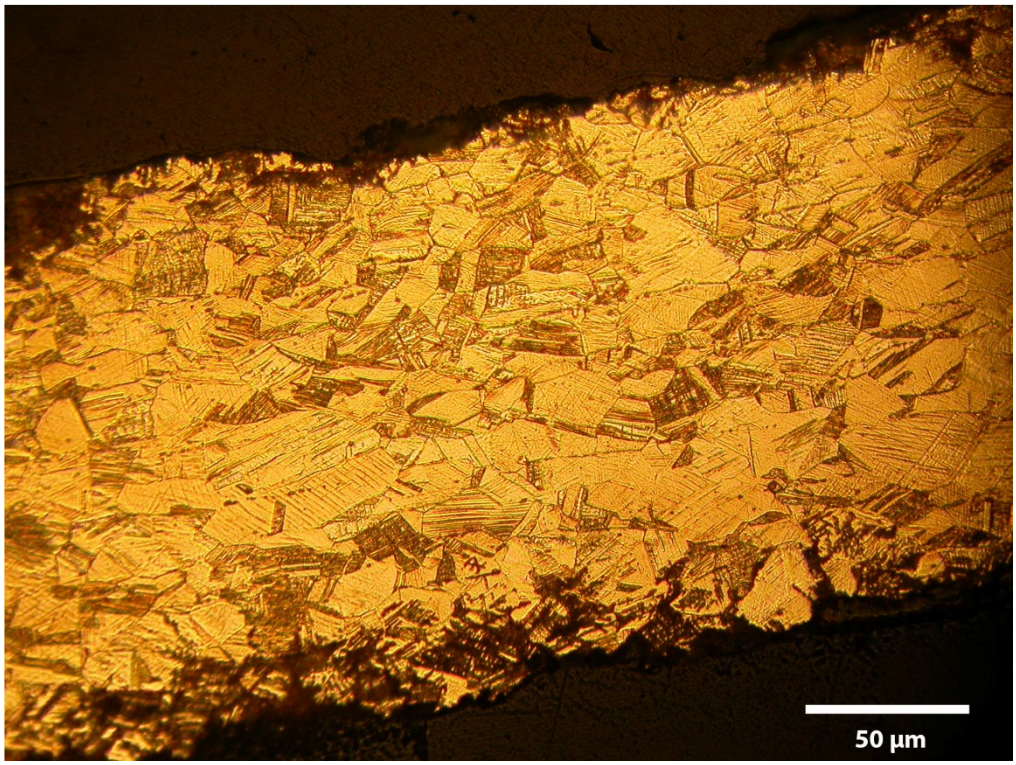


Figure A3.3 CC136

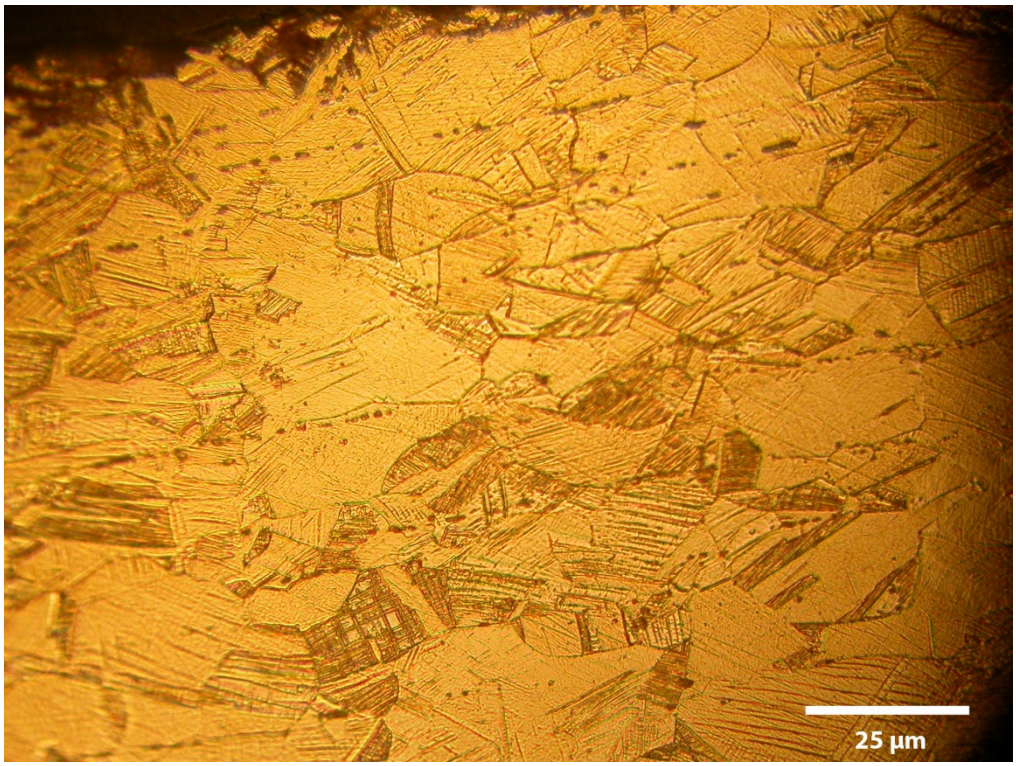


Figure A3.4 CC136

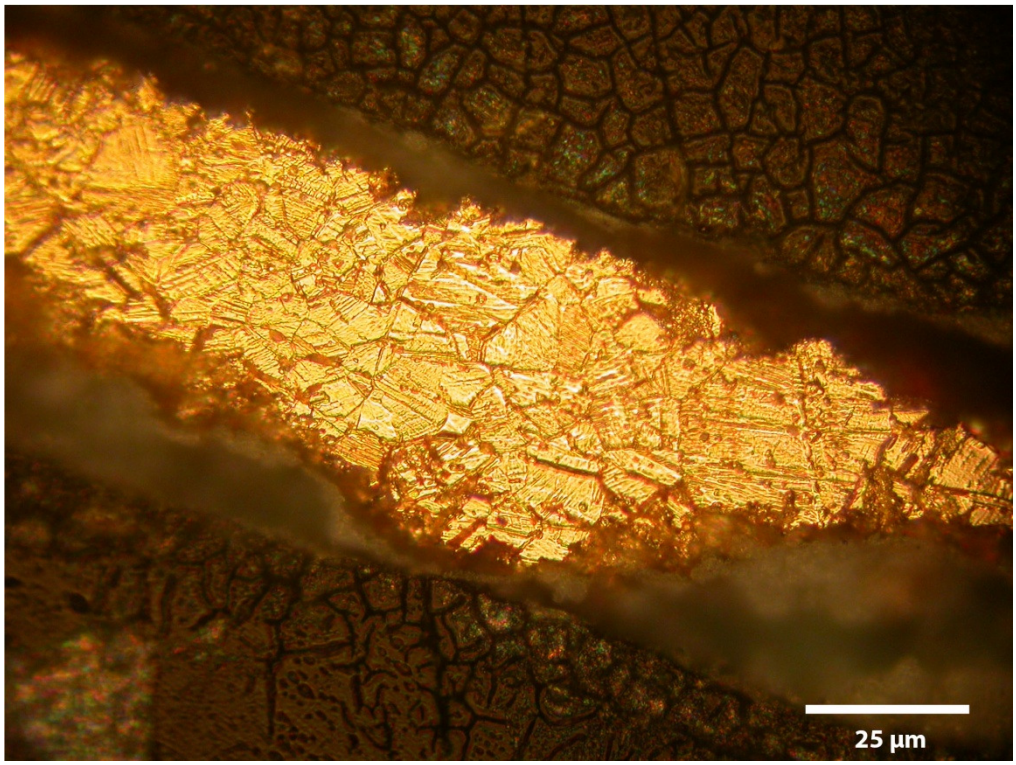


Figure A3.5 CC153

A3.2 Ham Hill

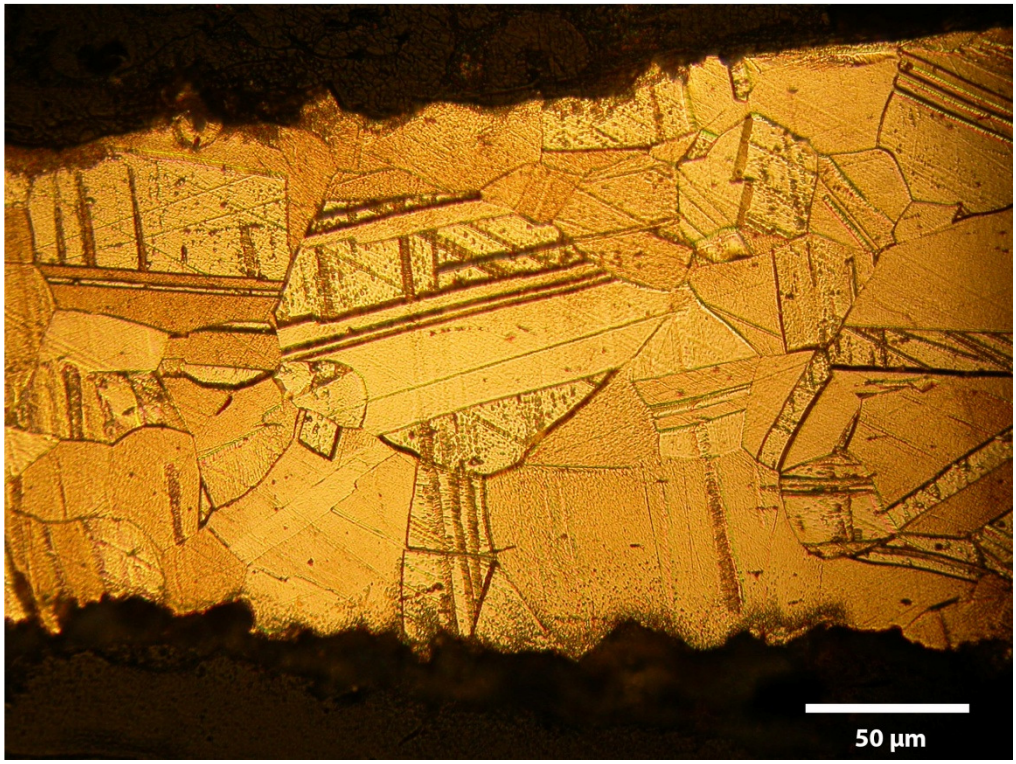


Figure A3.6 HamH E16

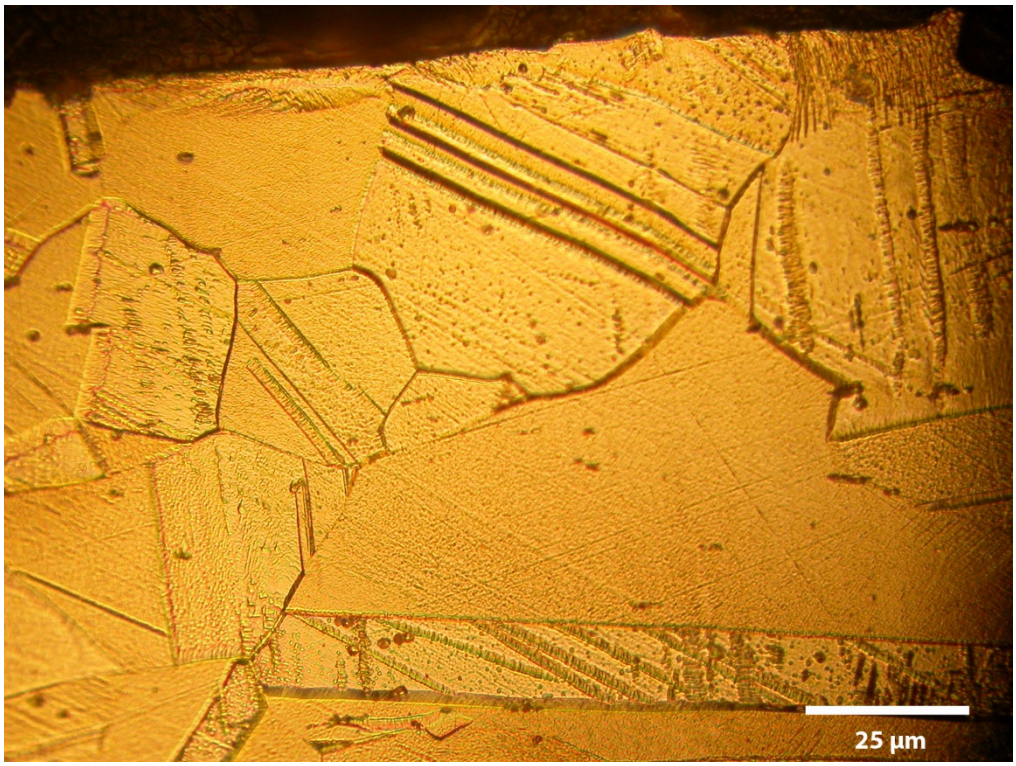


Figure A3.7 HamHE16

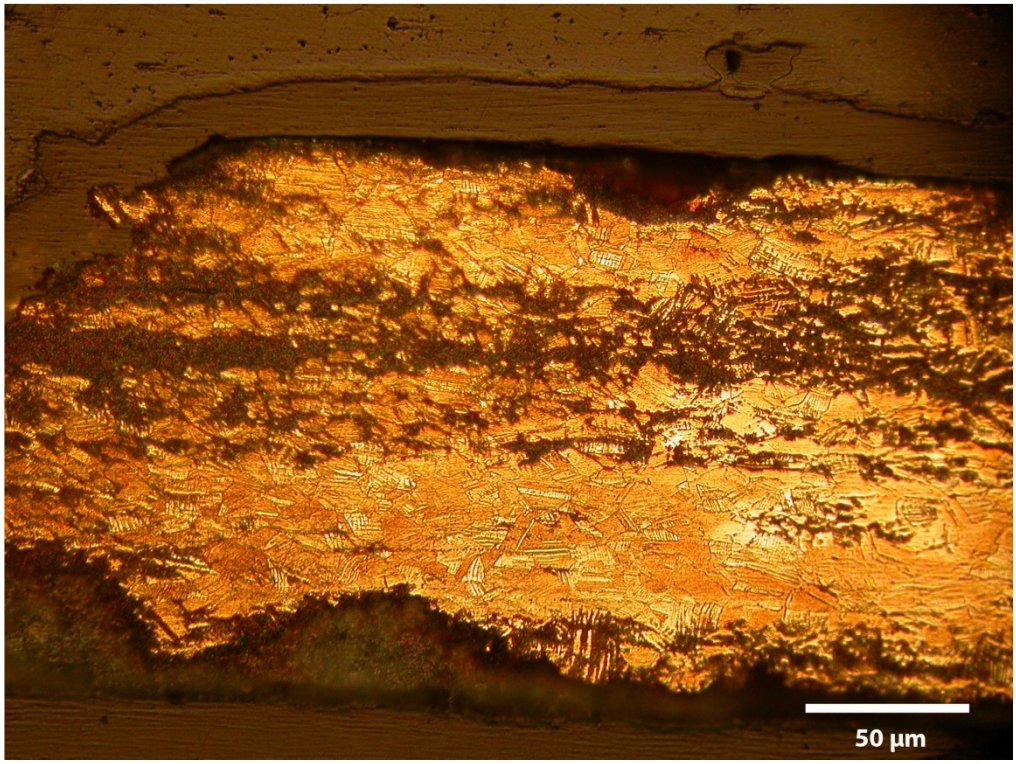


Figure A3.8 HamH A1276

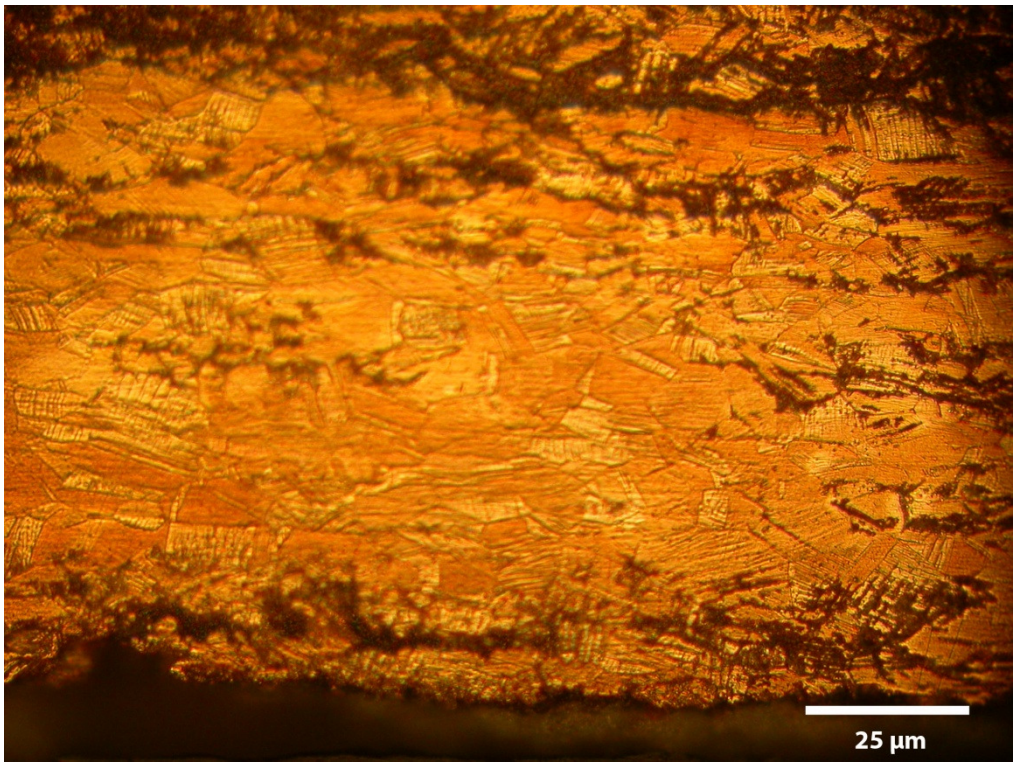


Figure A3.9 HamH A1276

A3.3 Carlisle

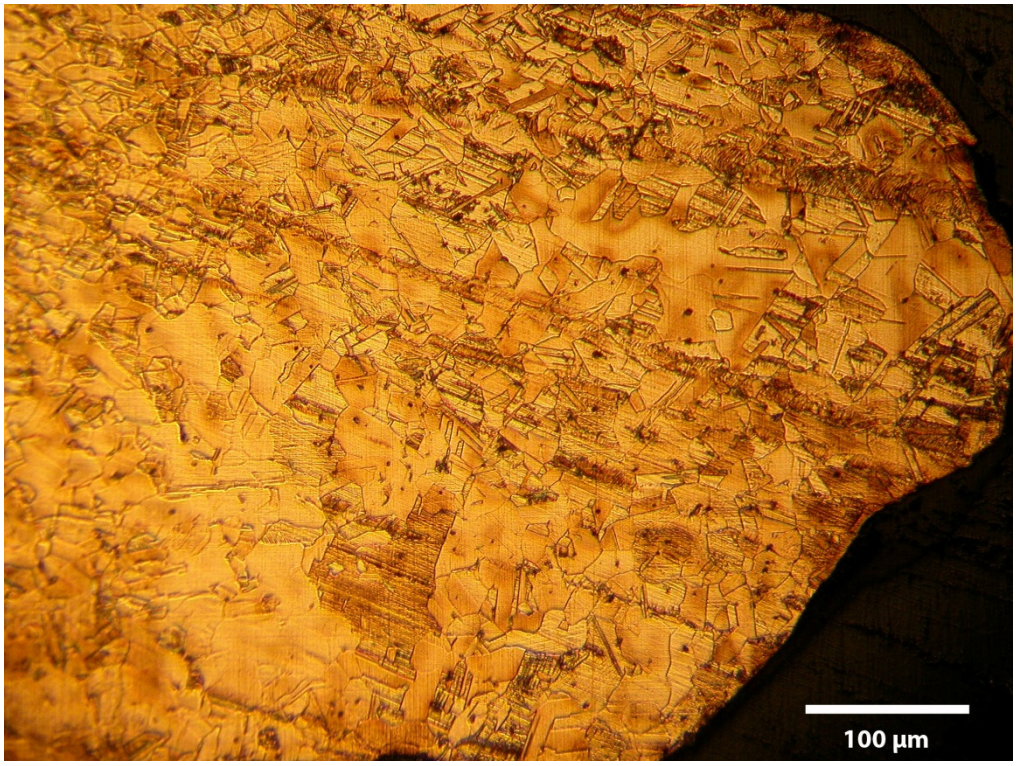


Figure A3.10 CSL2042

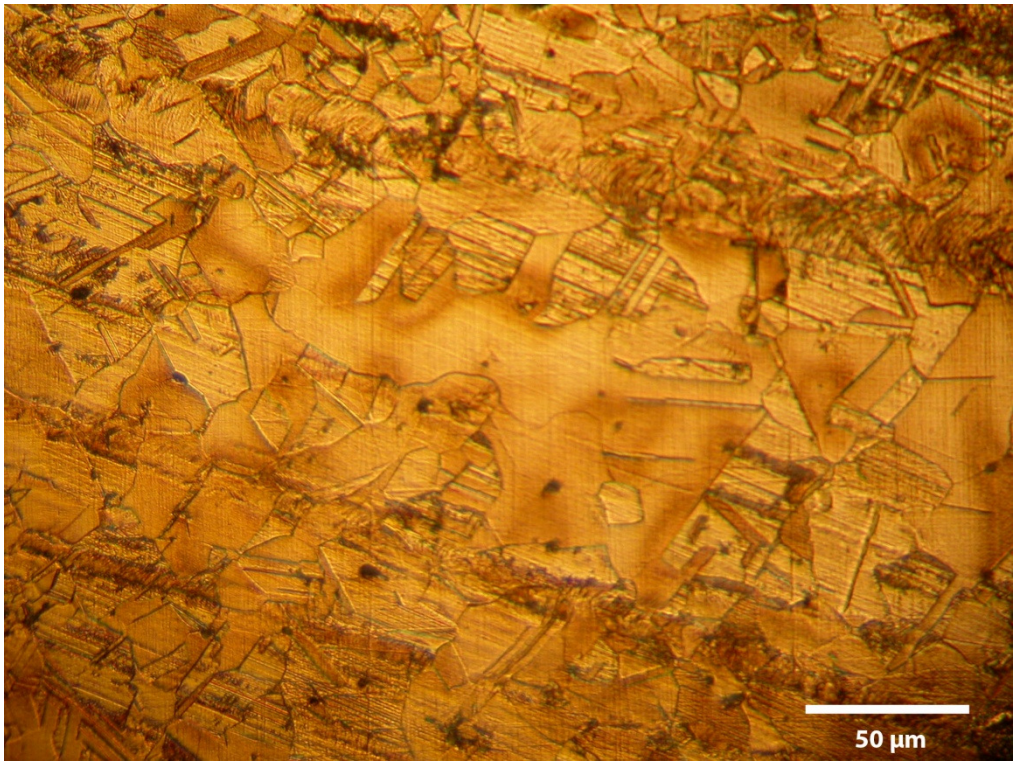


Figure A3.11 CSL2042

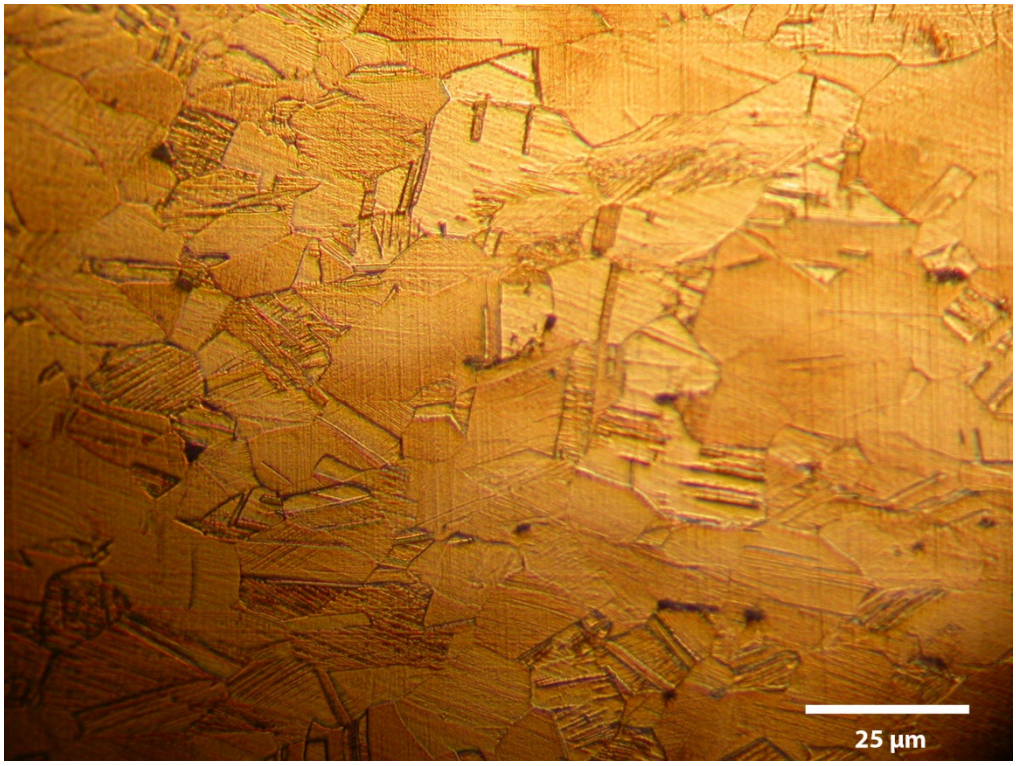


Figure A3.12 CSL2042

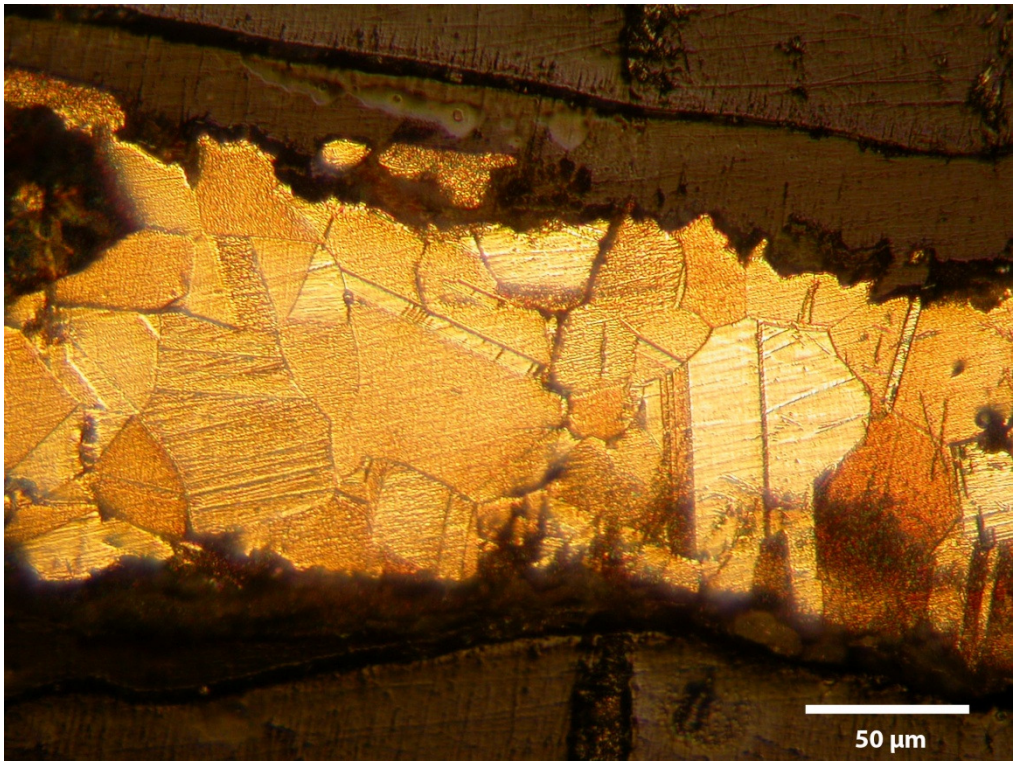
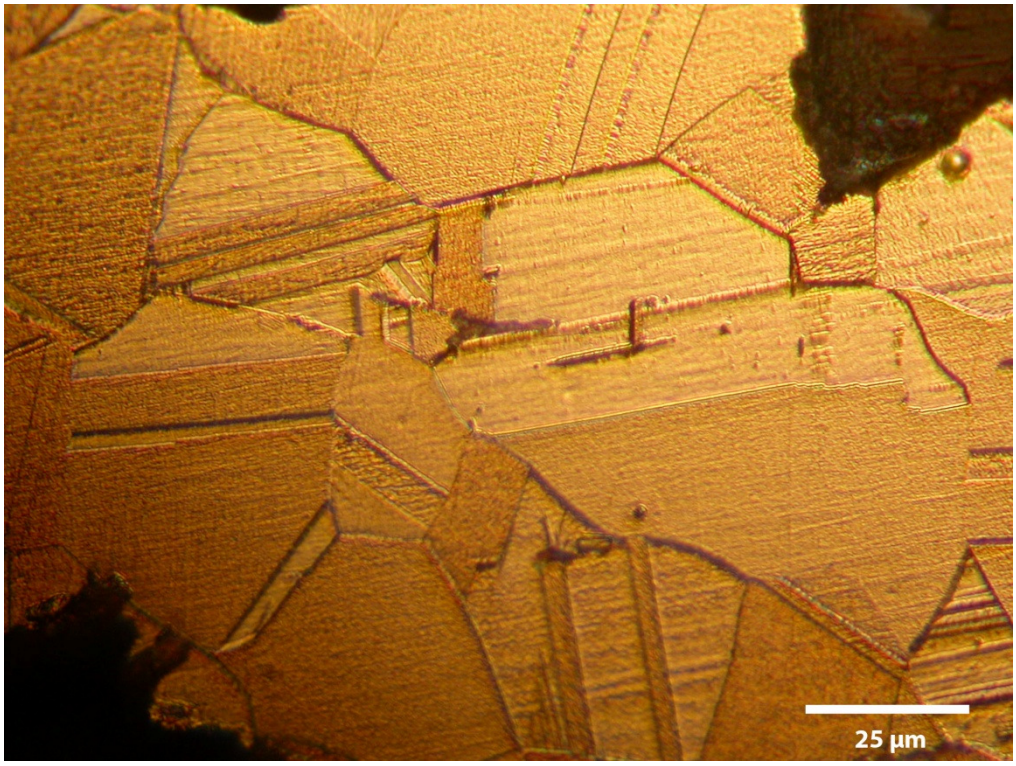


Figure A3.13 CSL2043



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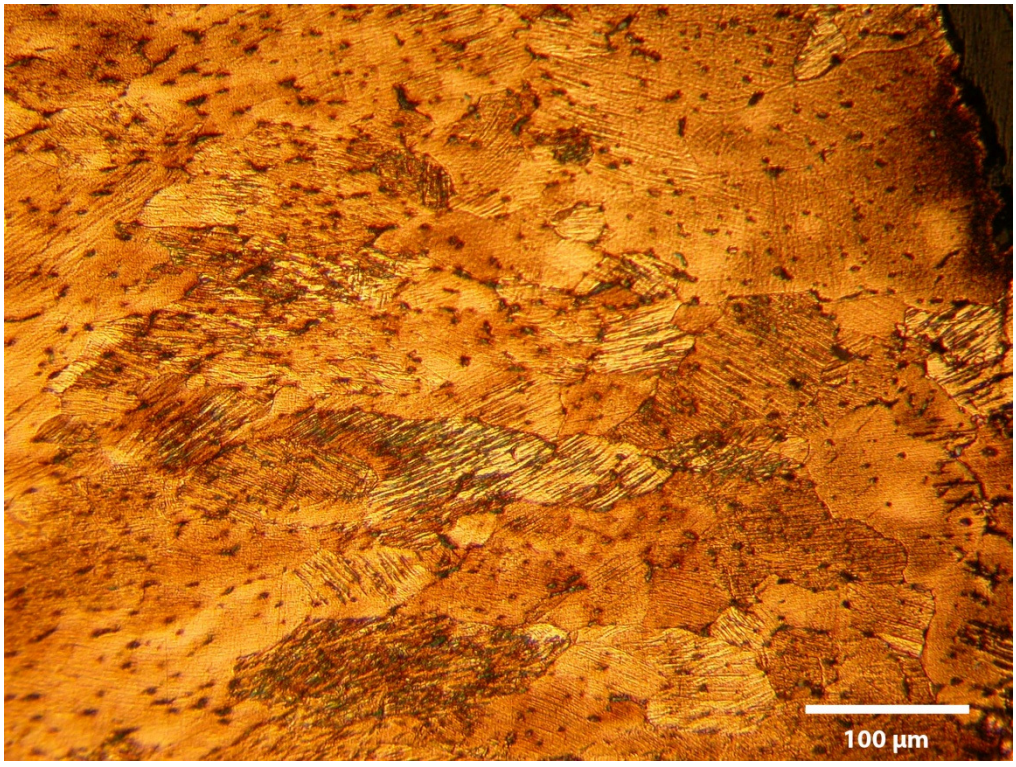
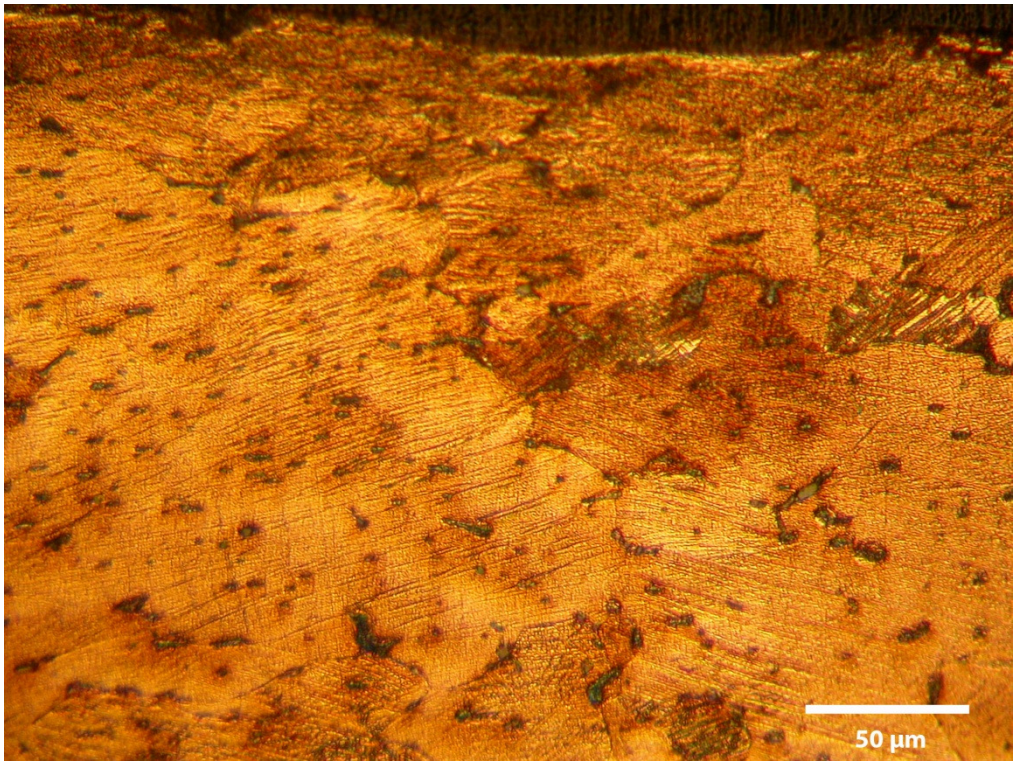


Figure A3.15 CSL2788



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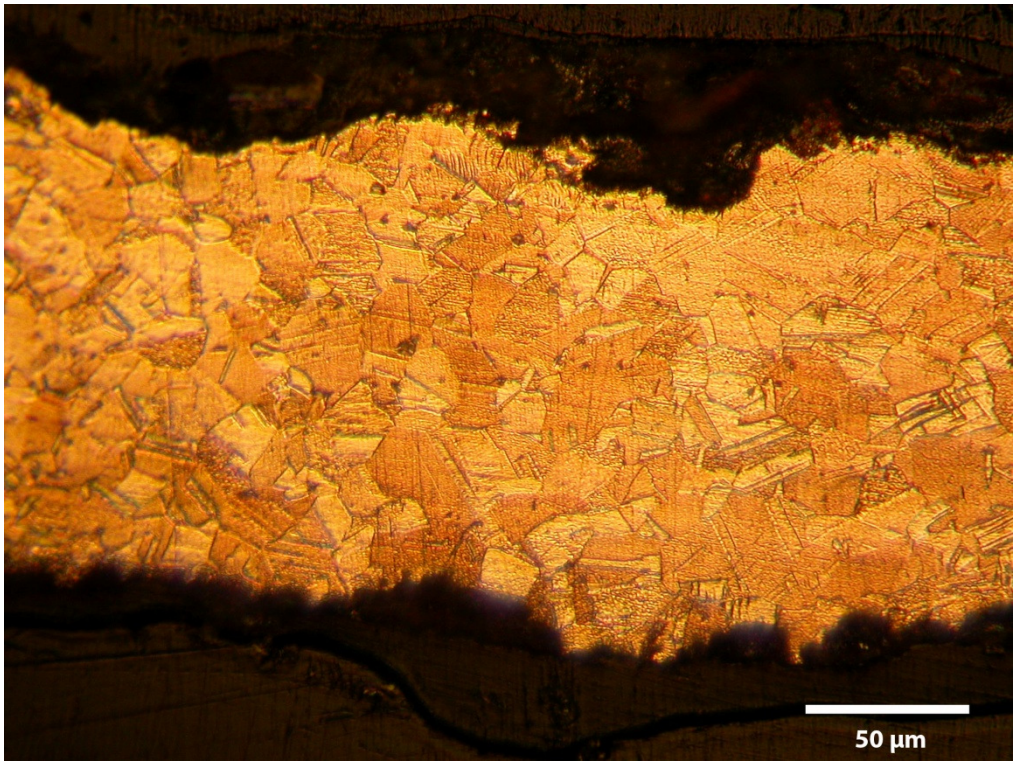
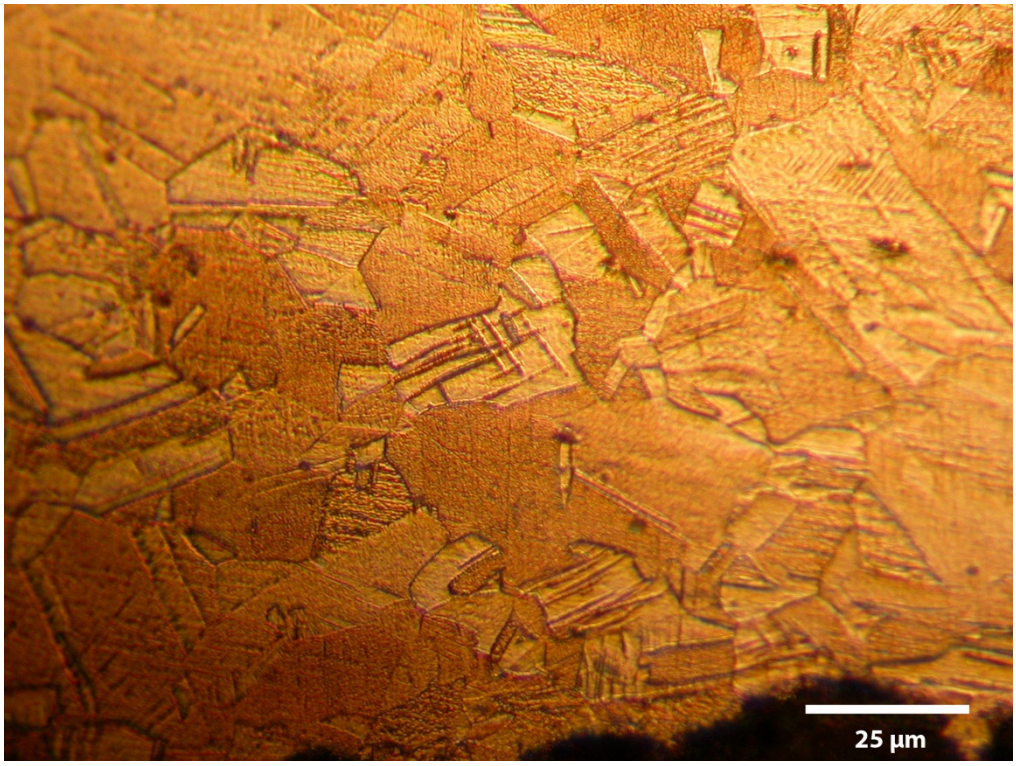


Figure A3.17 CSL3946



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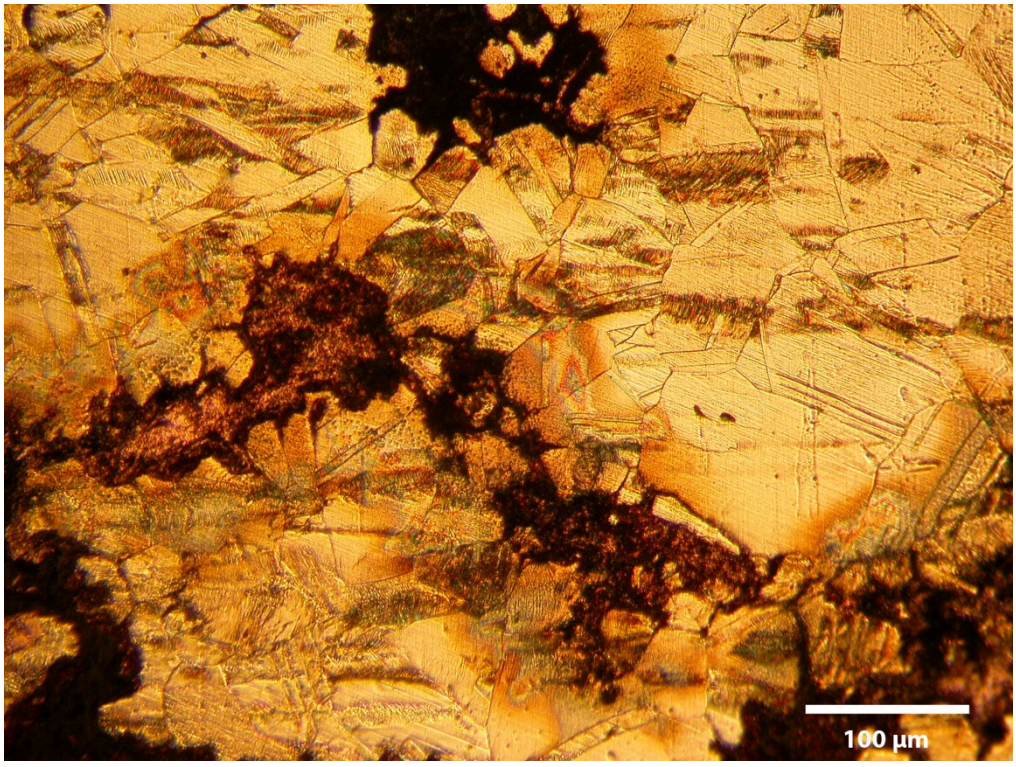

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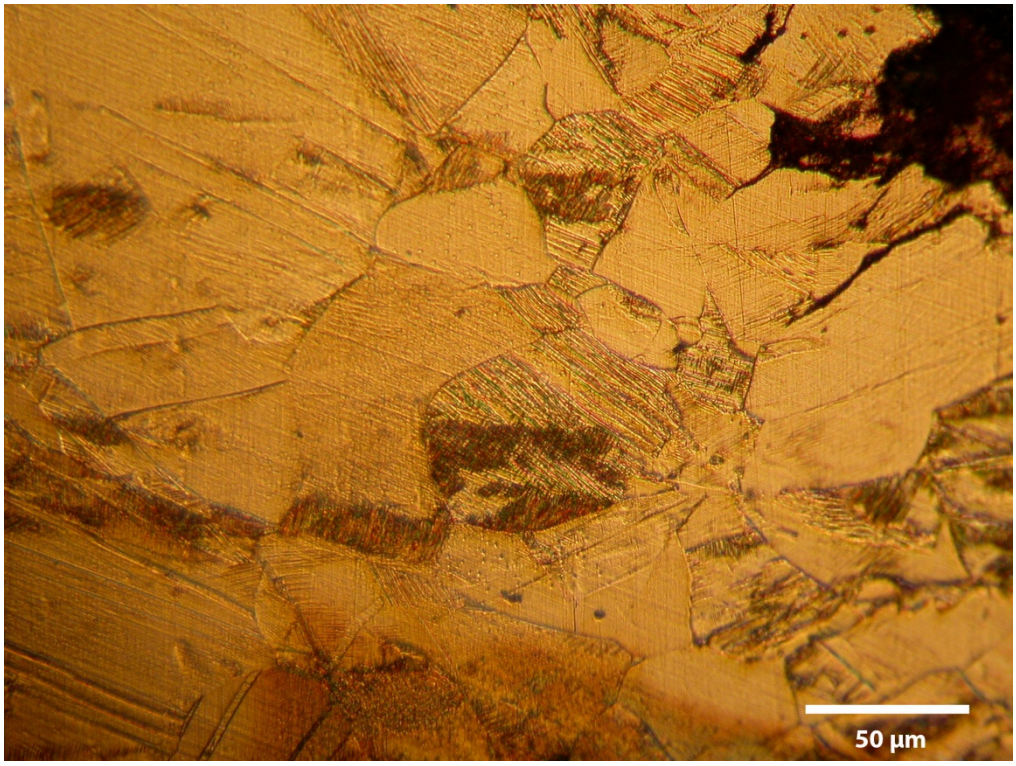

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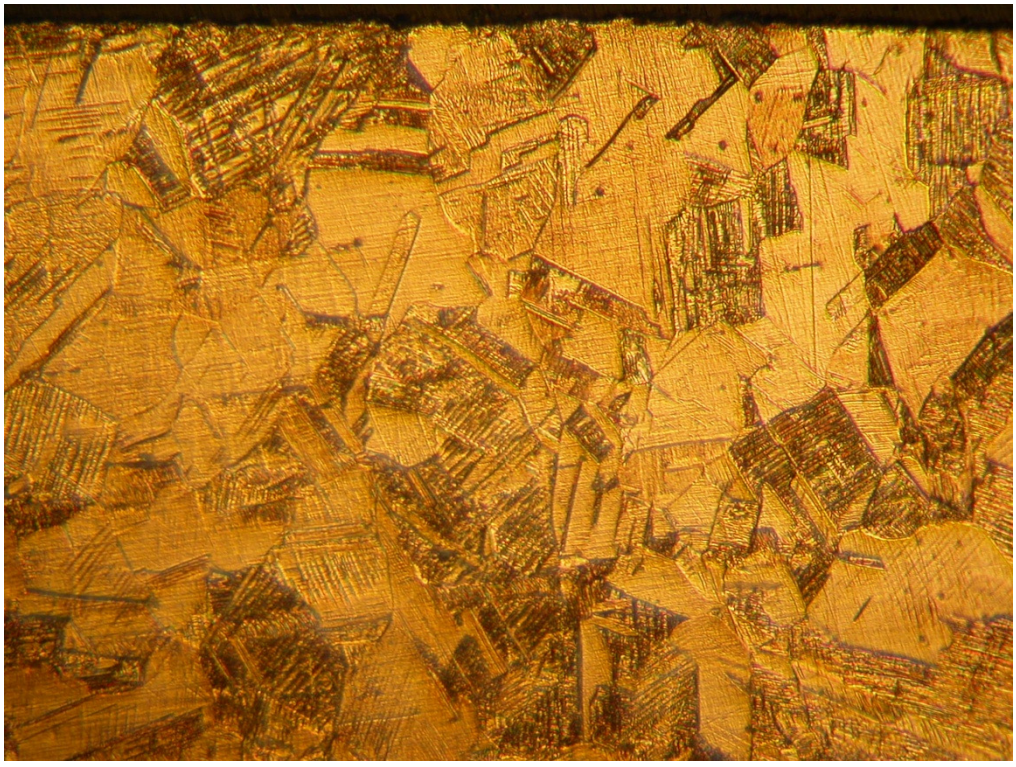

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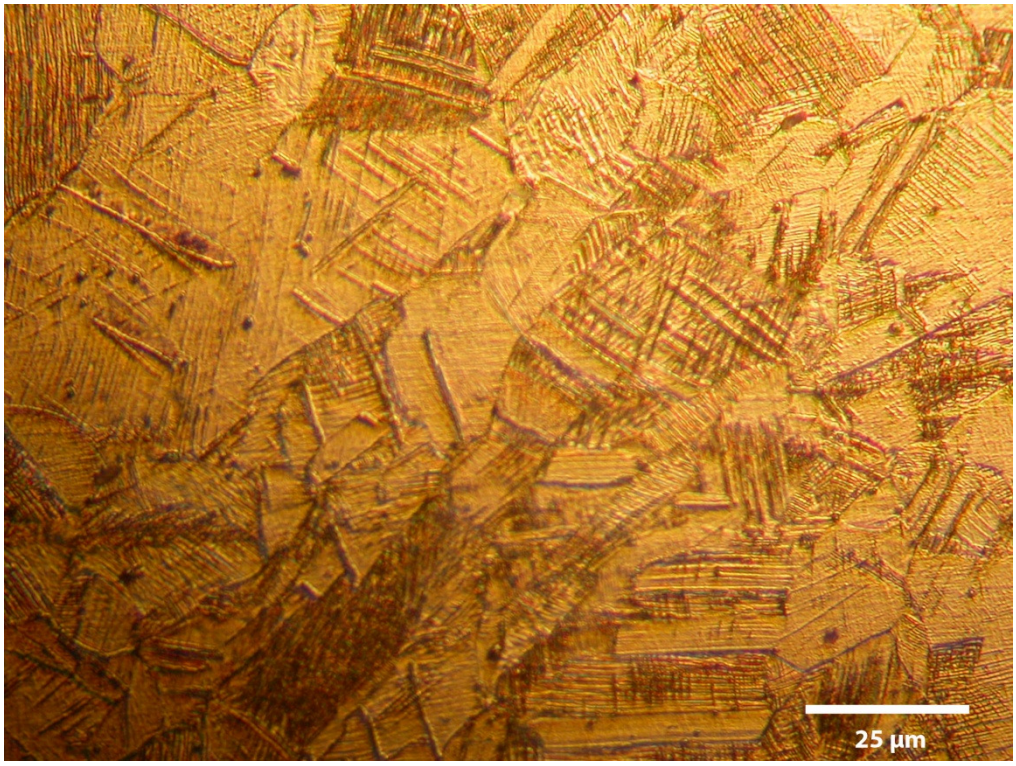

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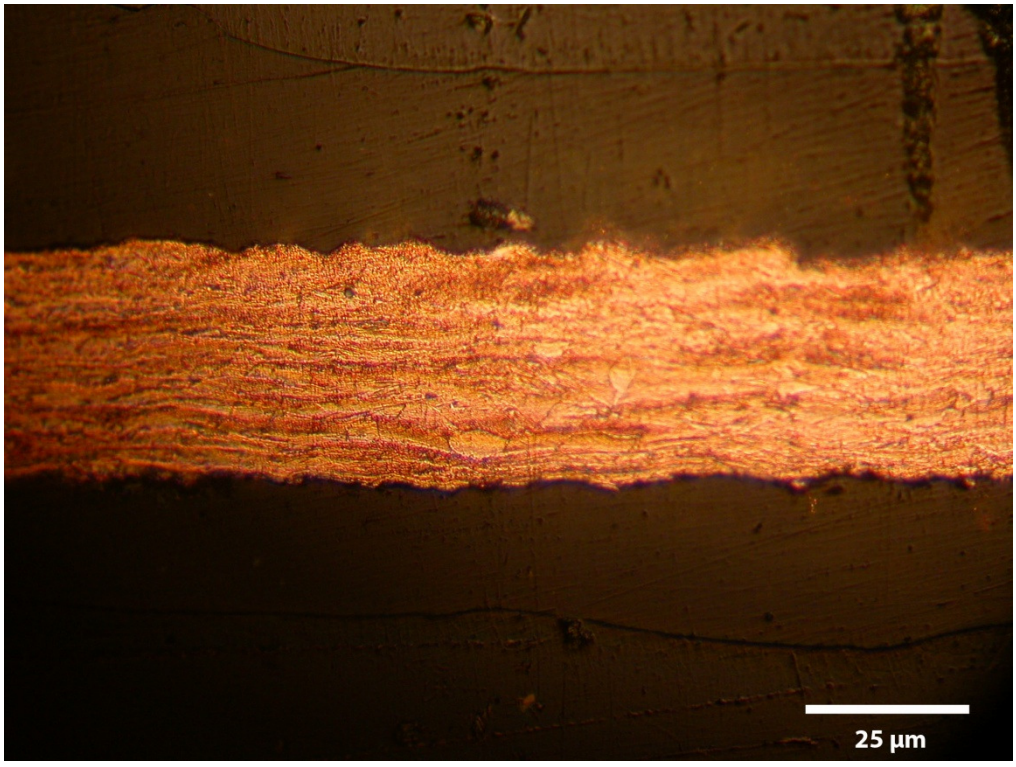

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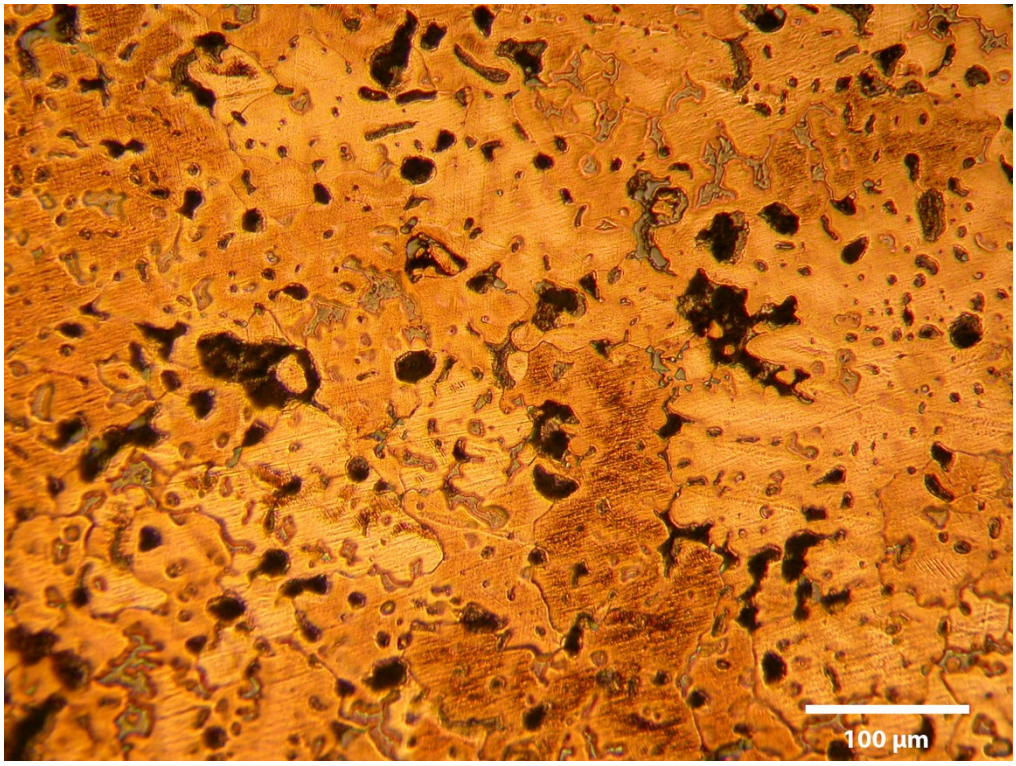

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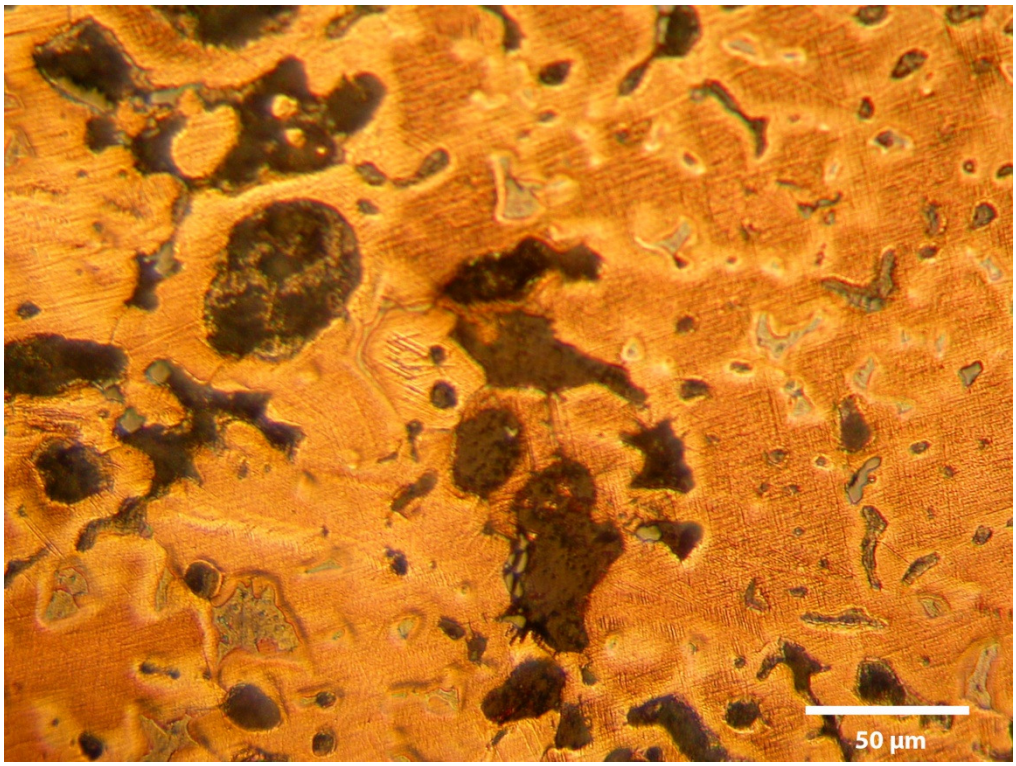
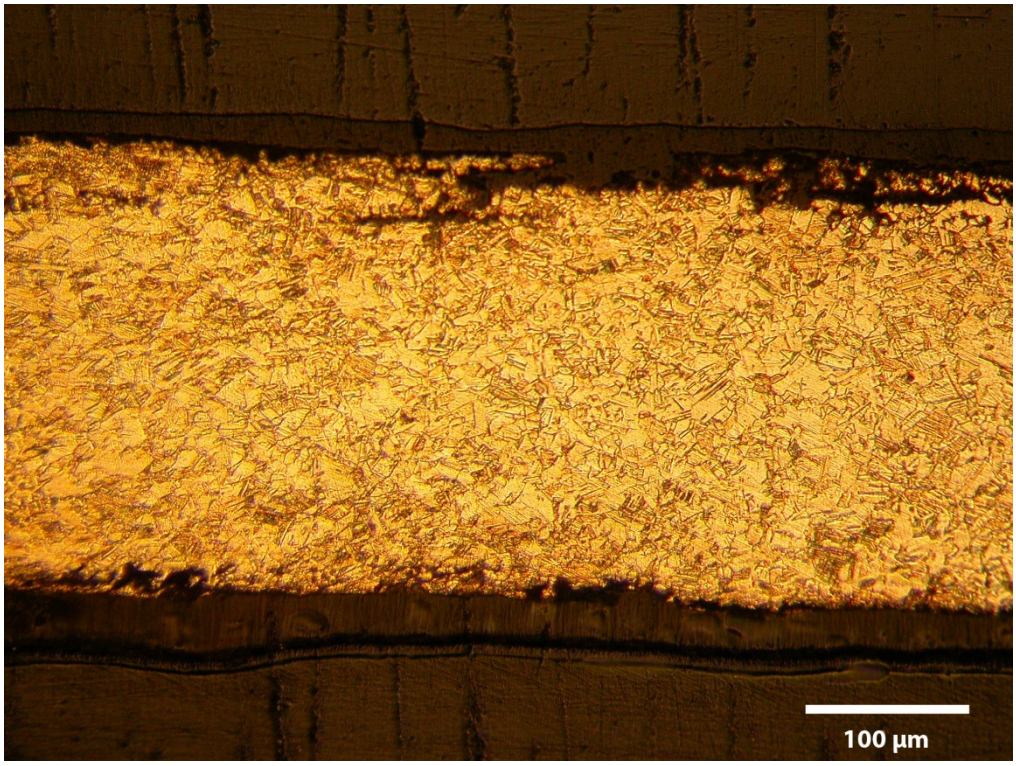


Figure A3.25 CSL6224

A3.4 Usk



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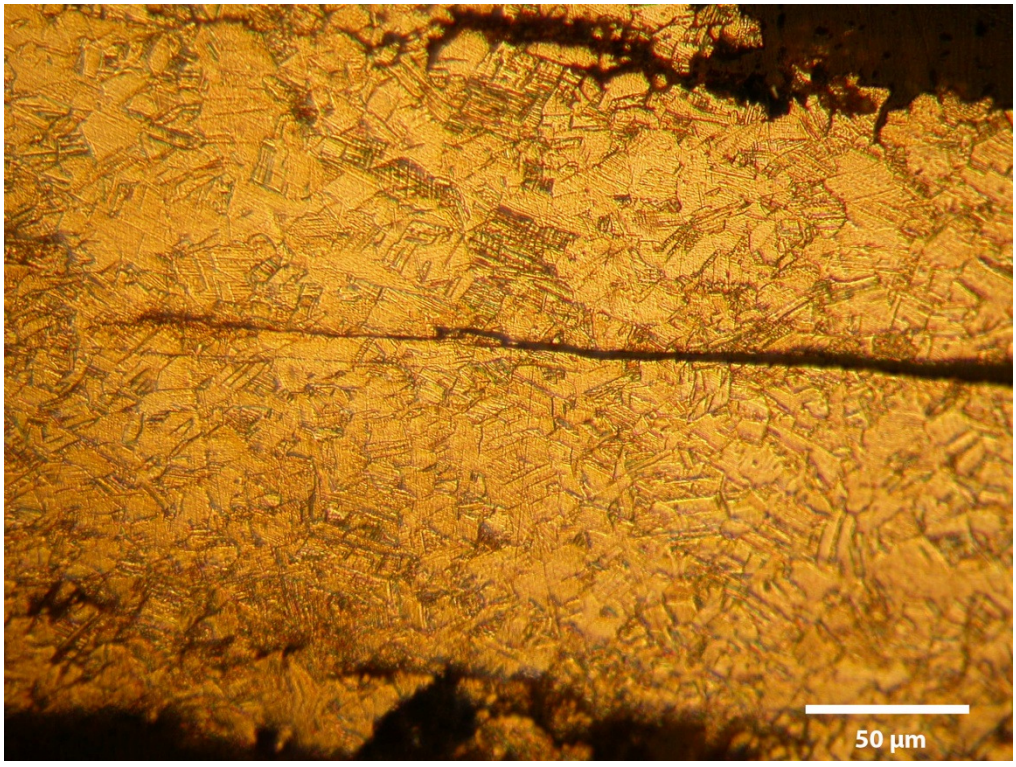

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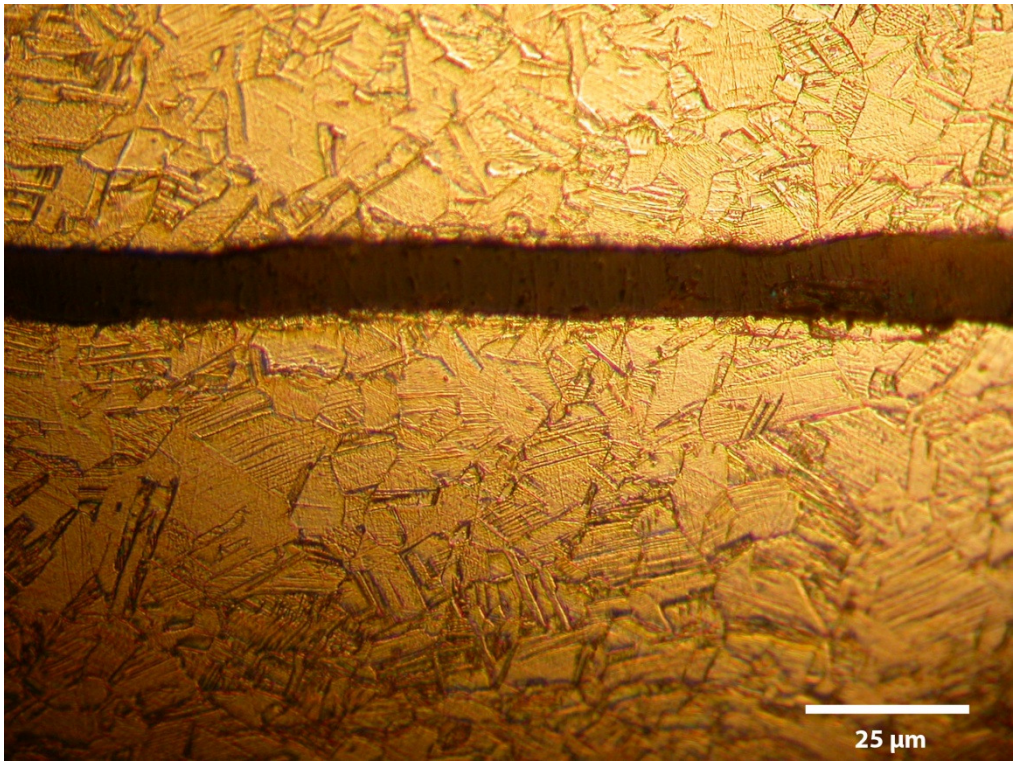

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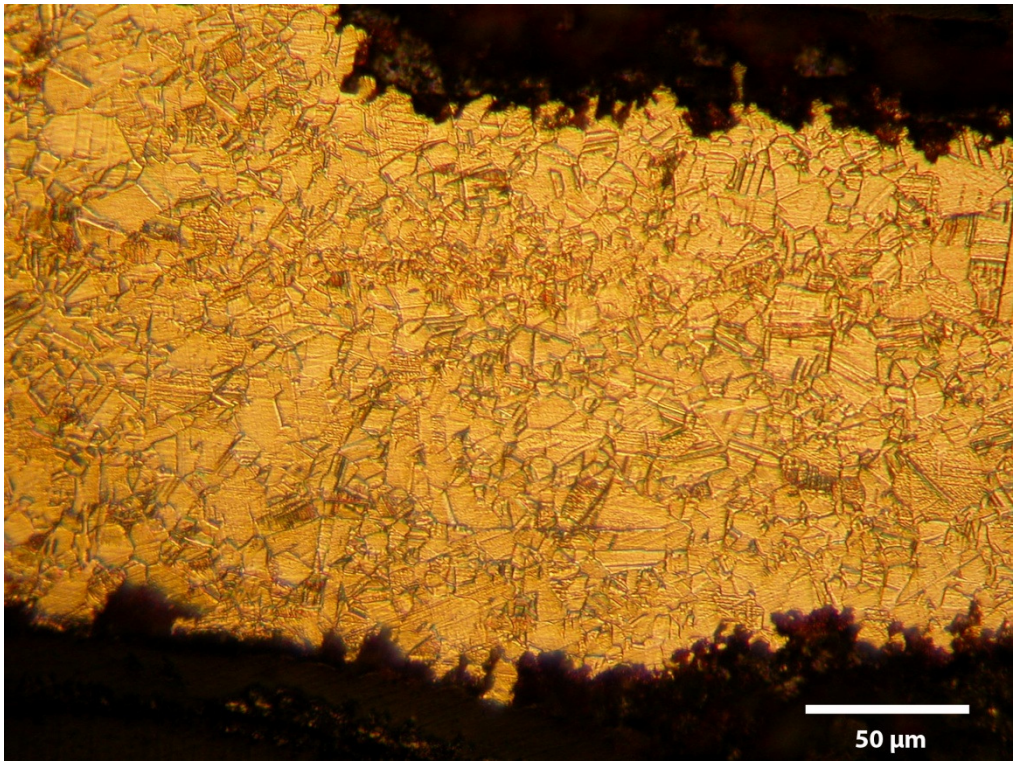

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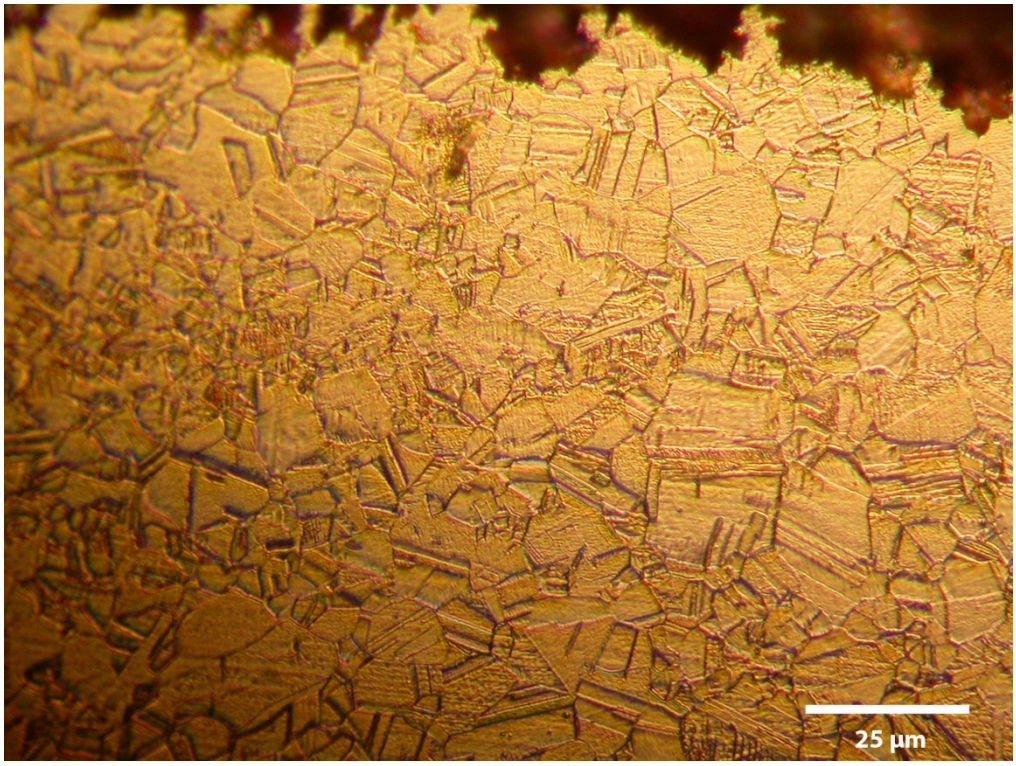

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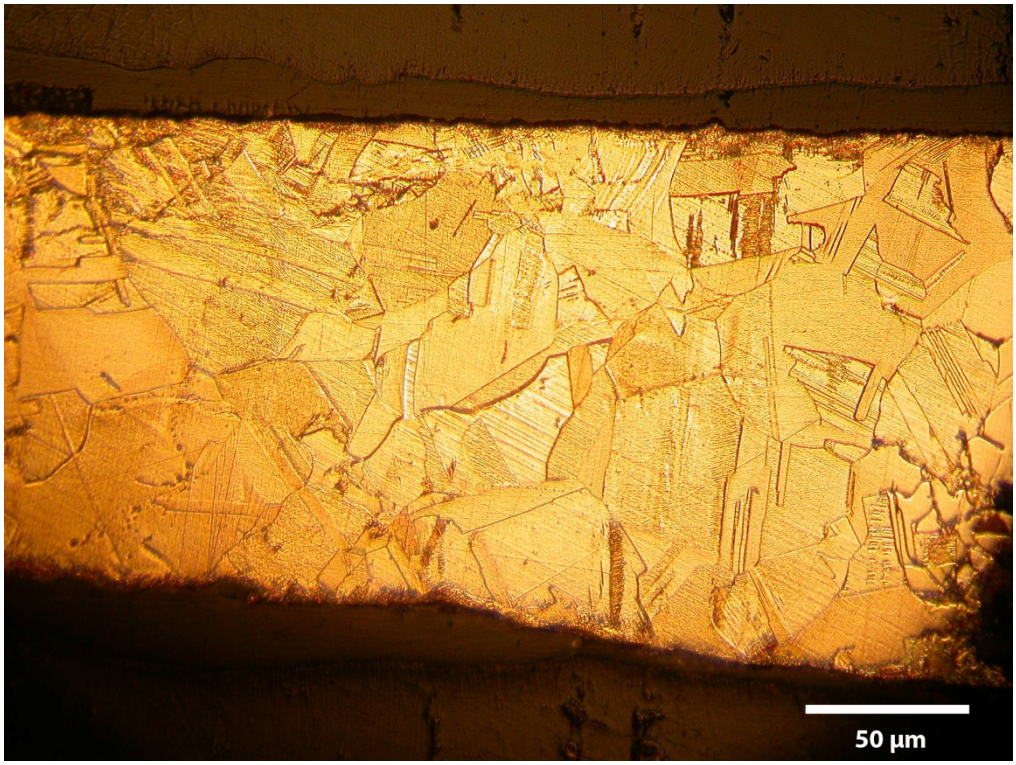
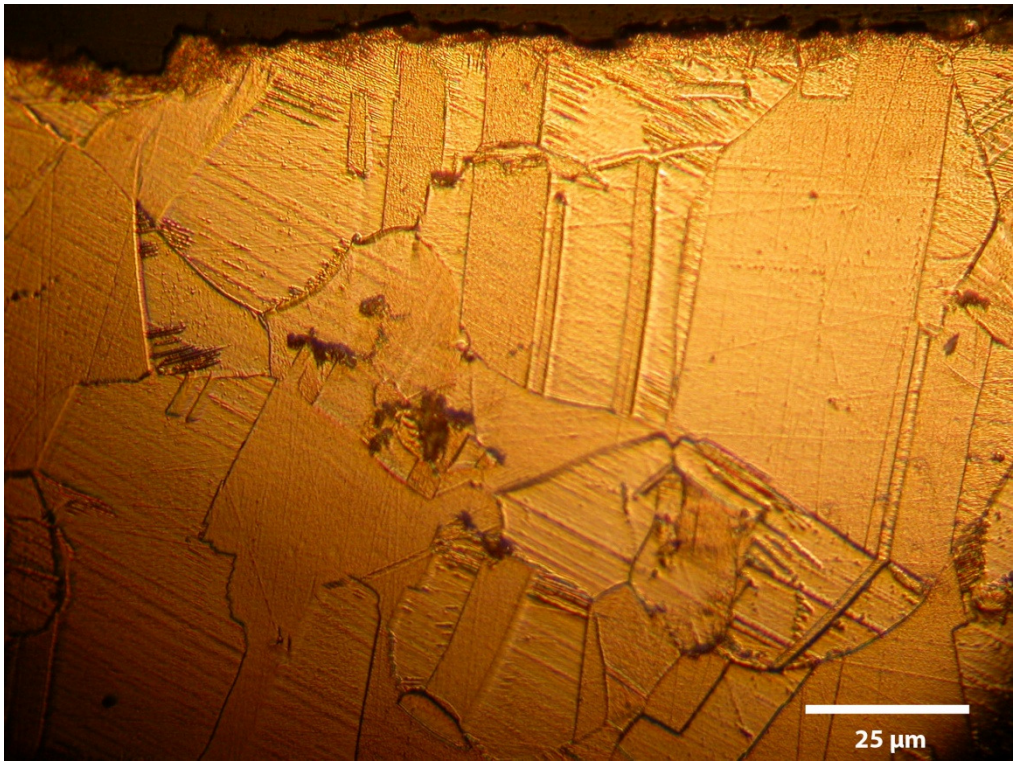


Figure A3.31 USKManF5N36



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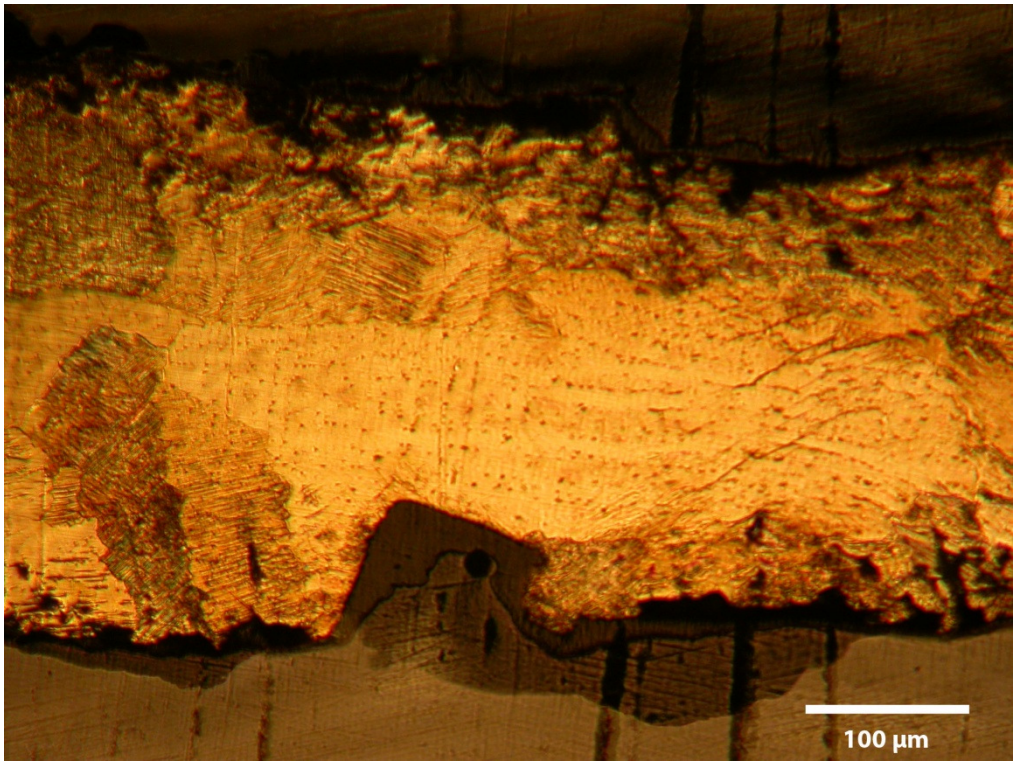
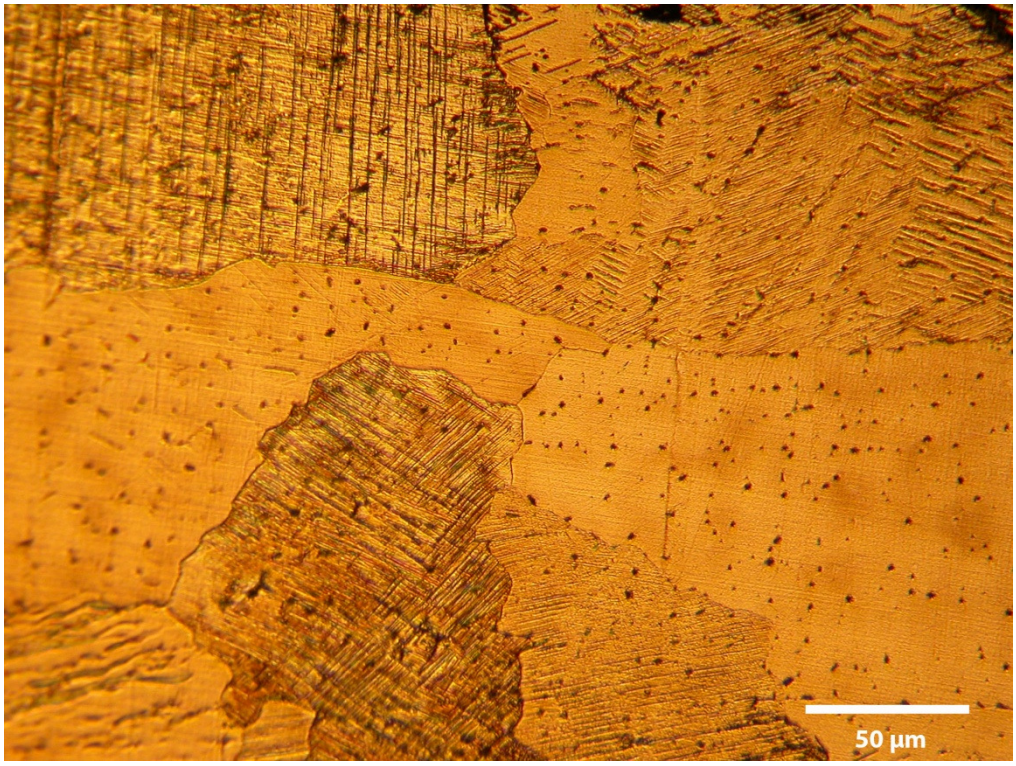


Figure A3.33 USKManP40N3



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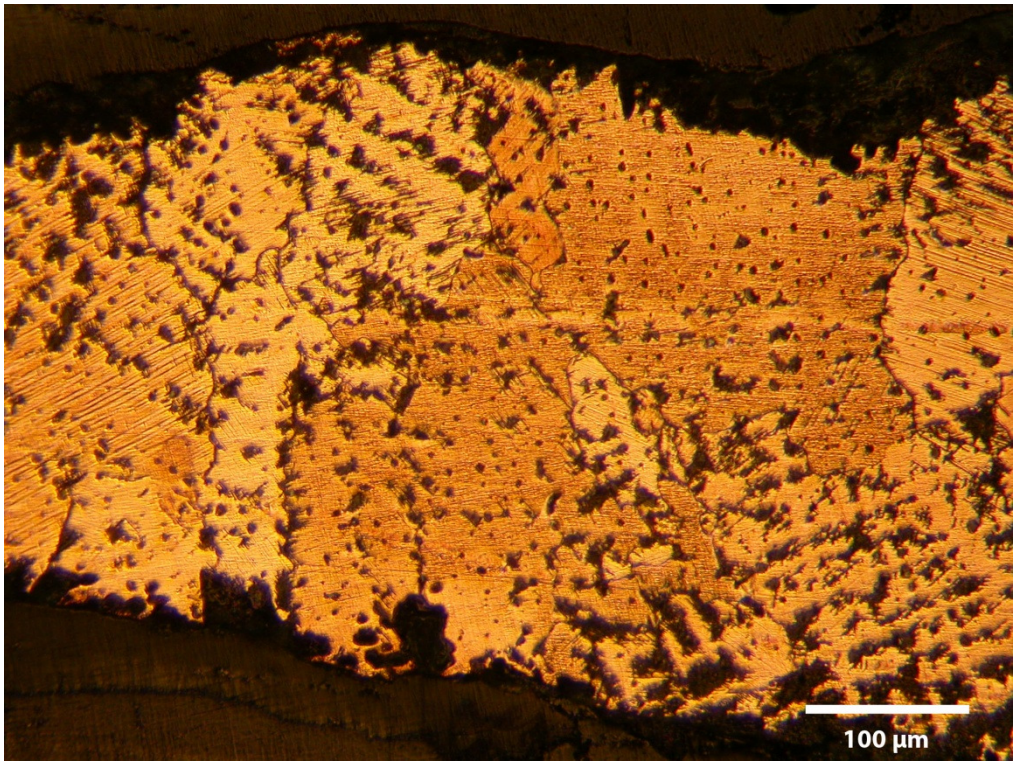

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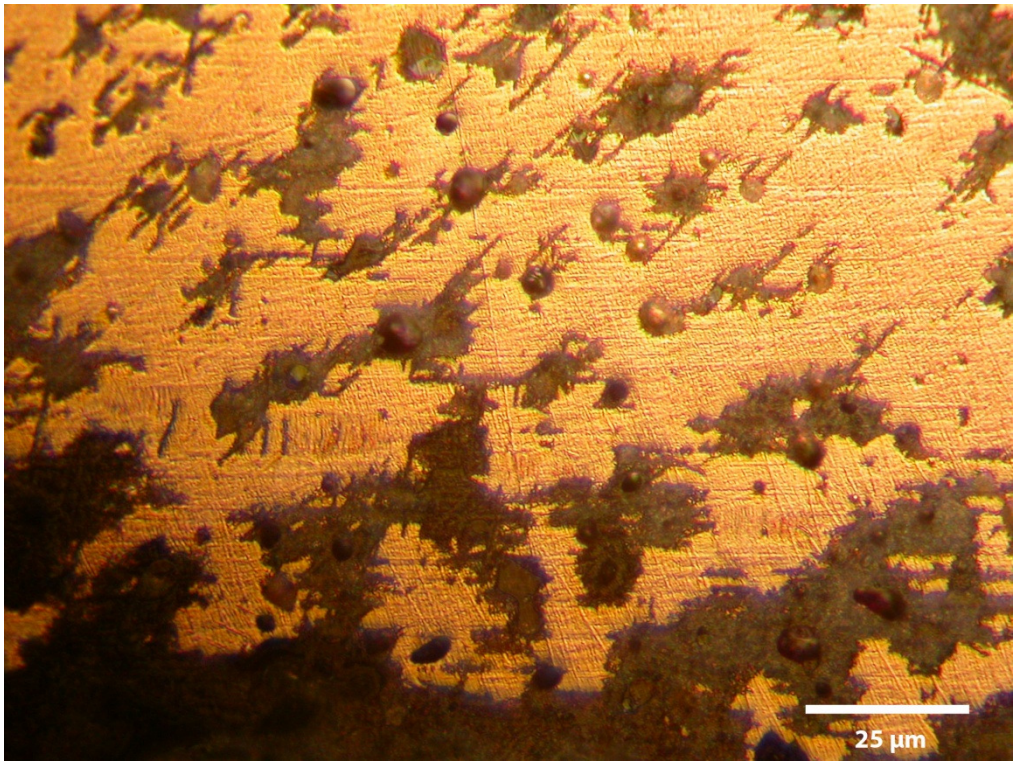

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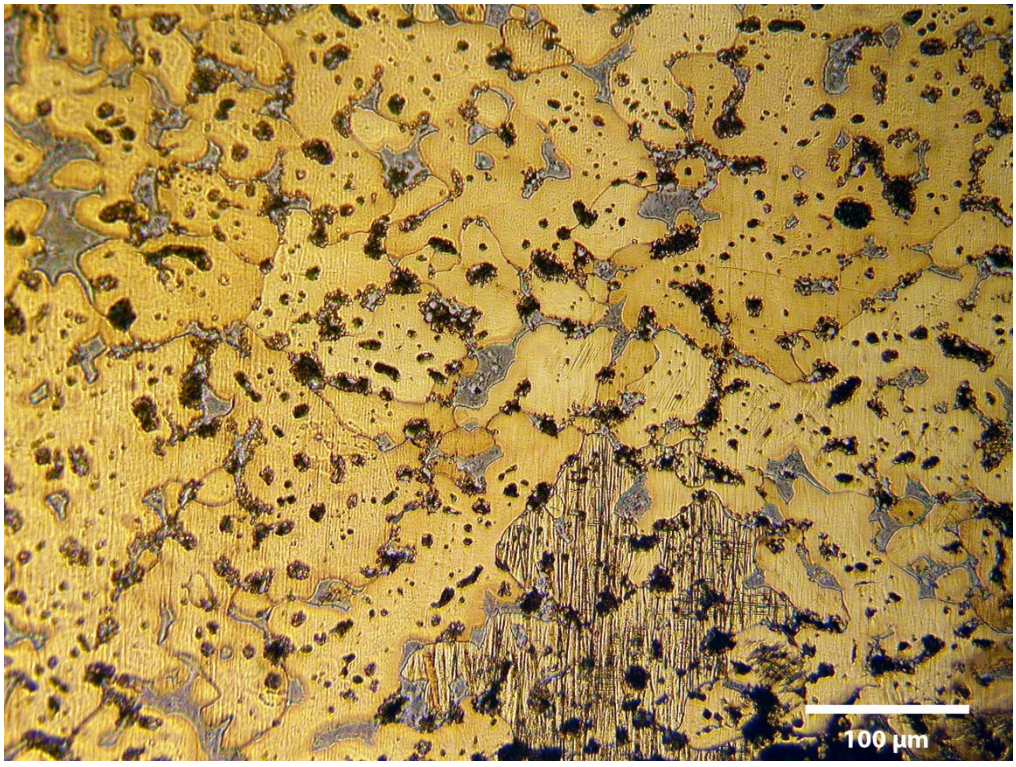
A3.5 Chester



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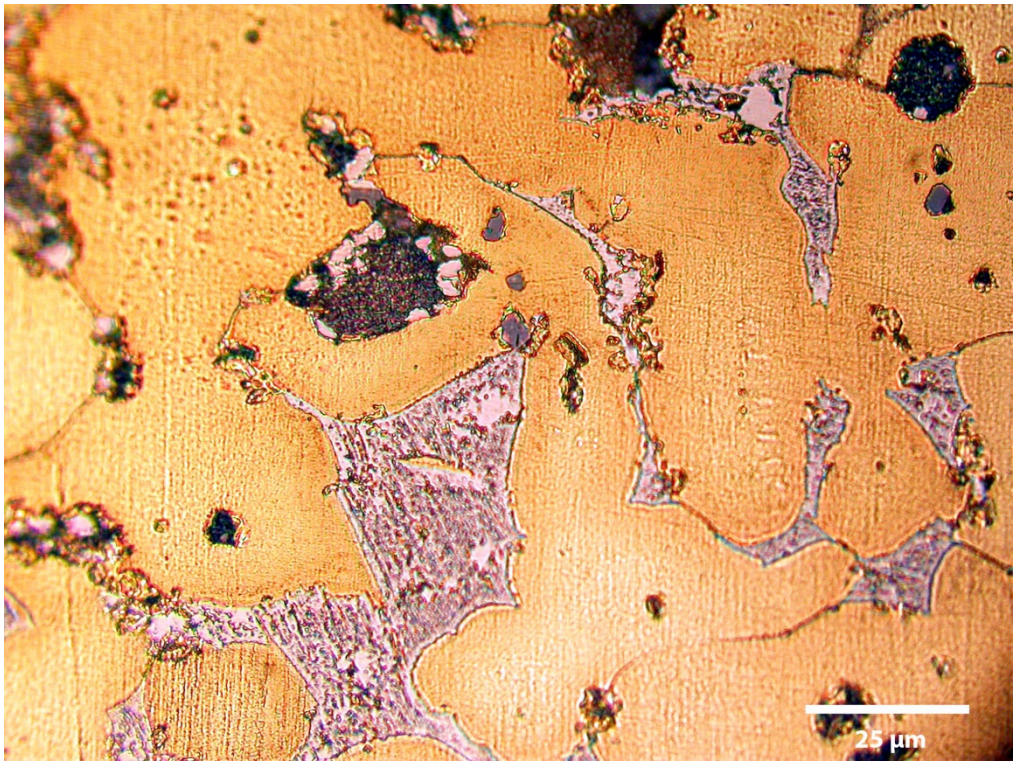

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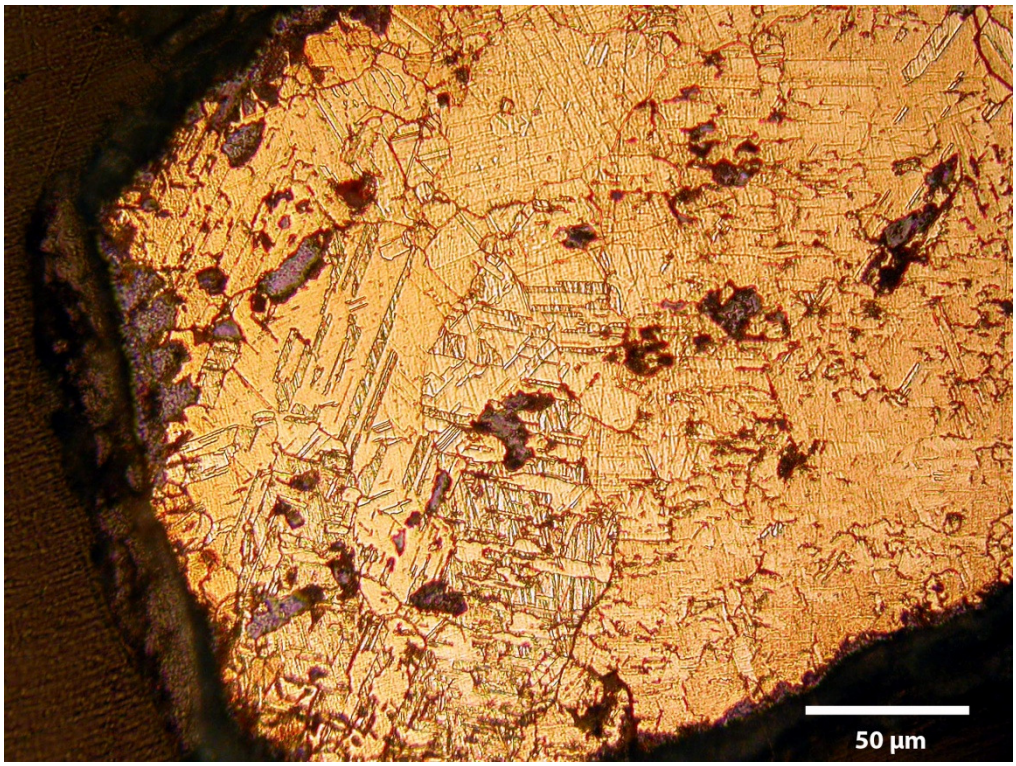

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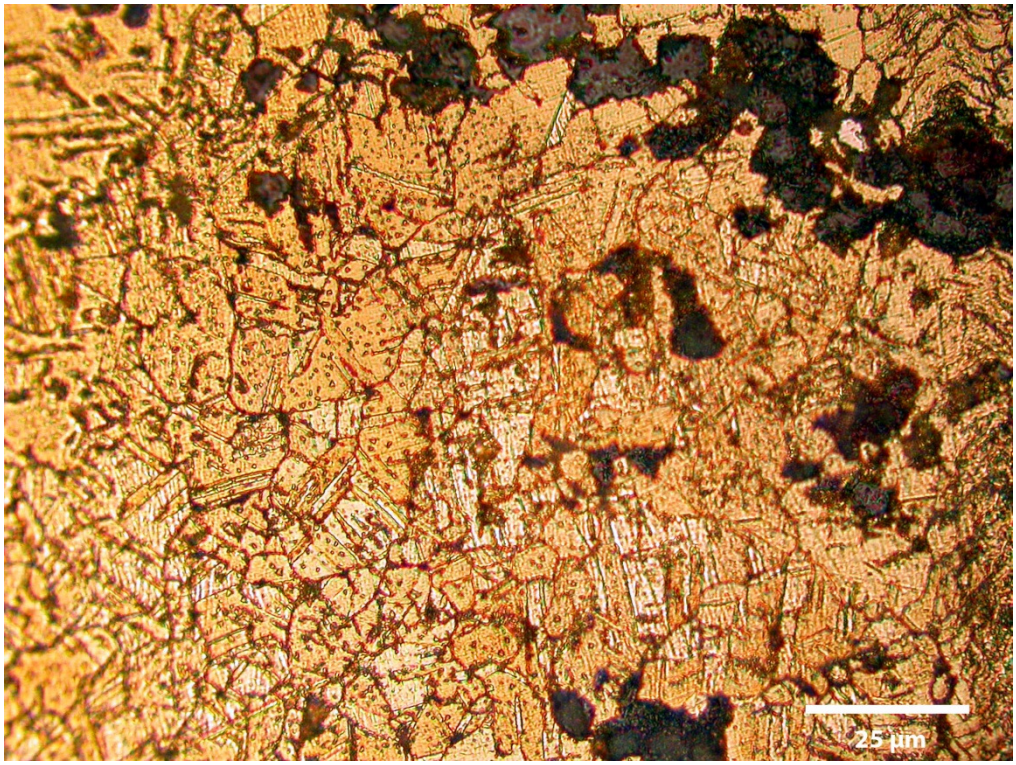

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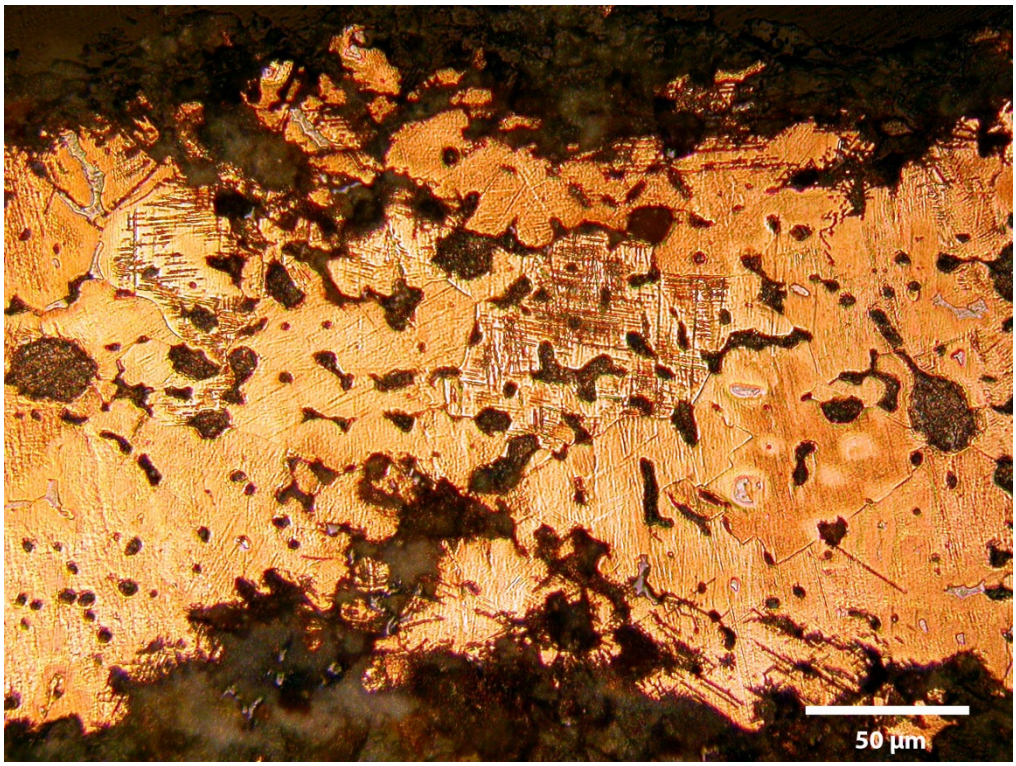

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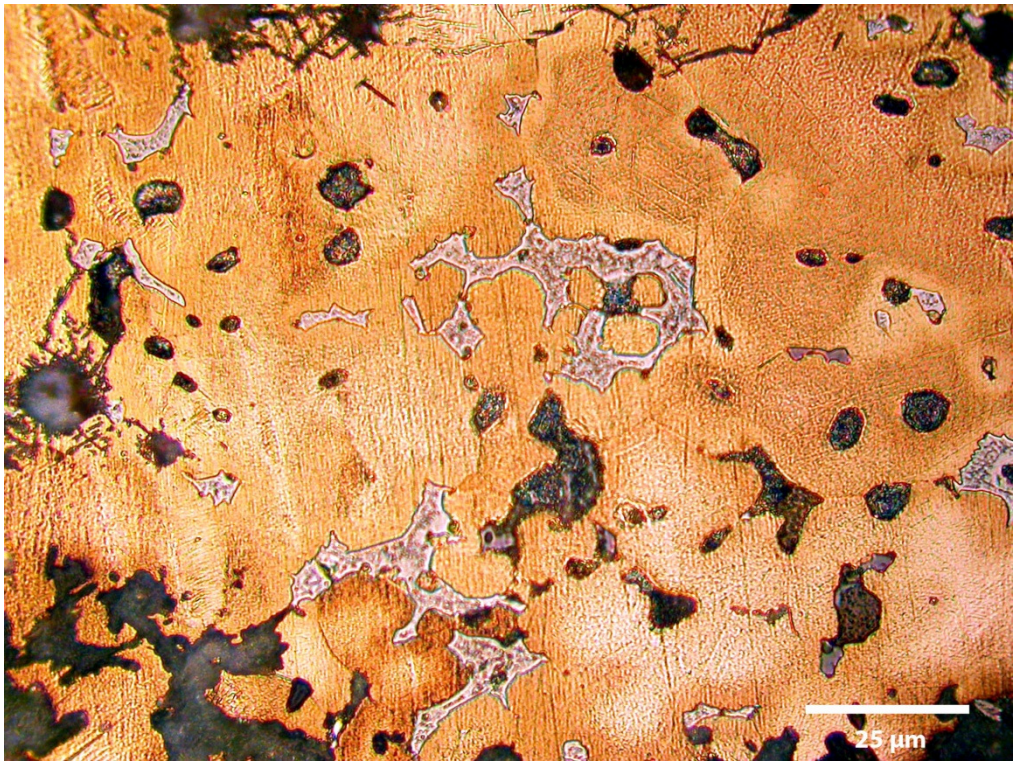

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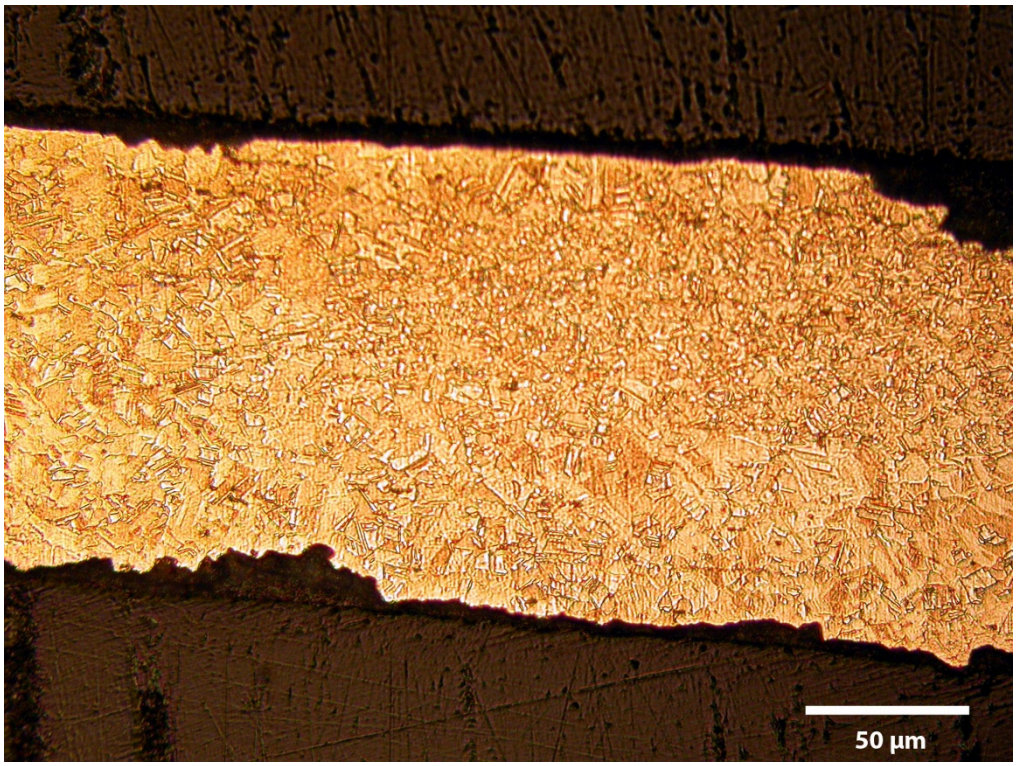

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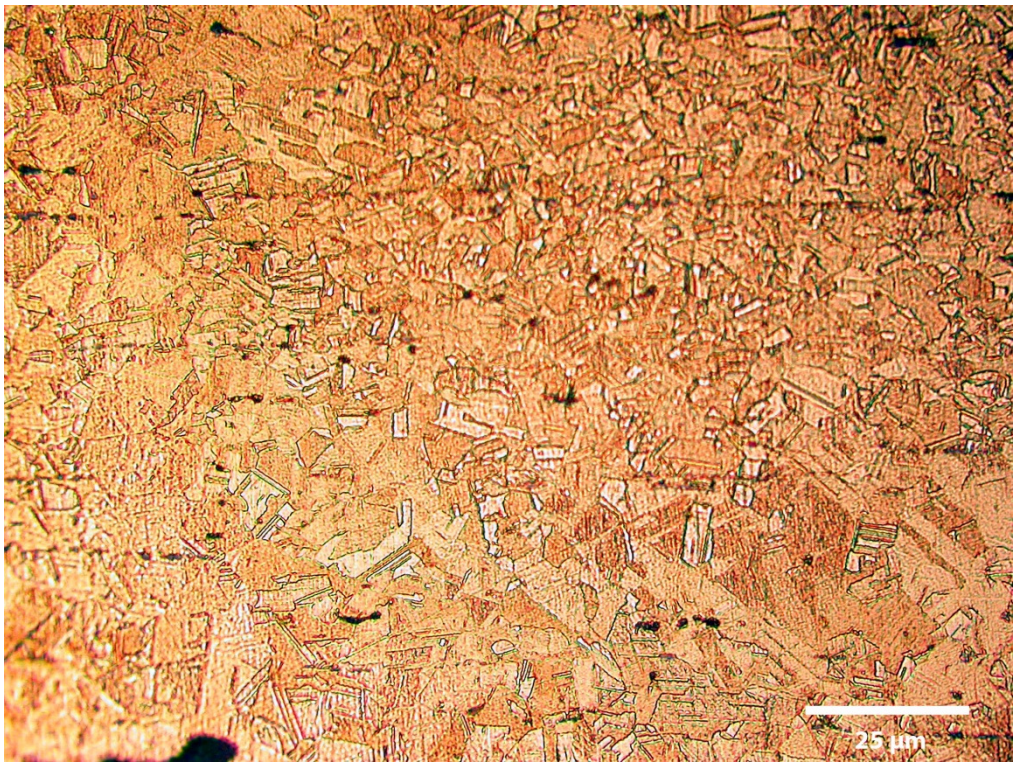

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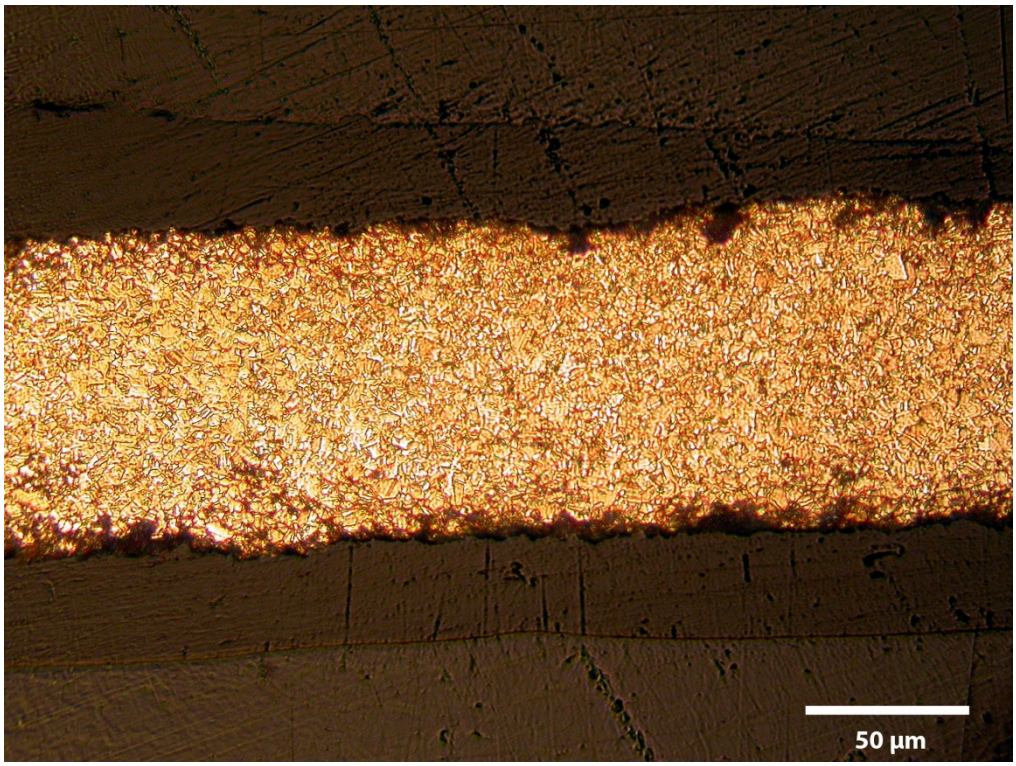

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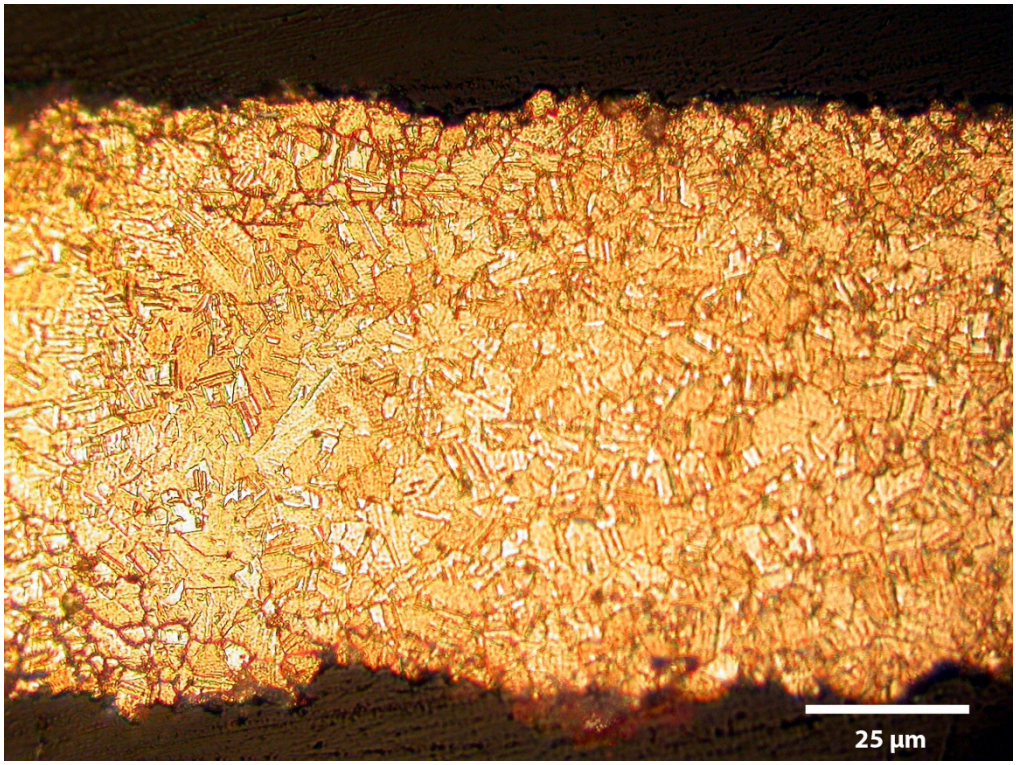

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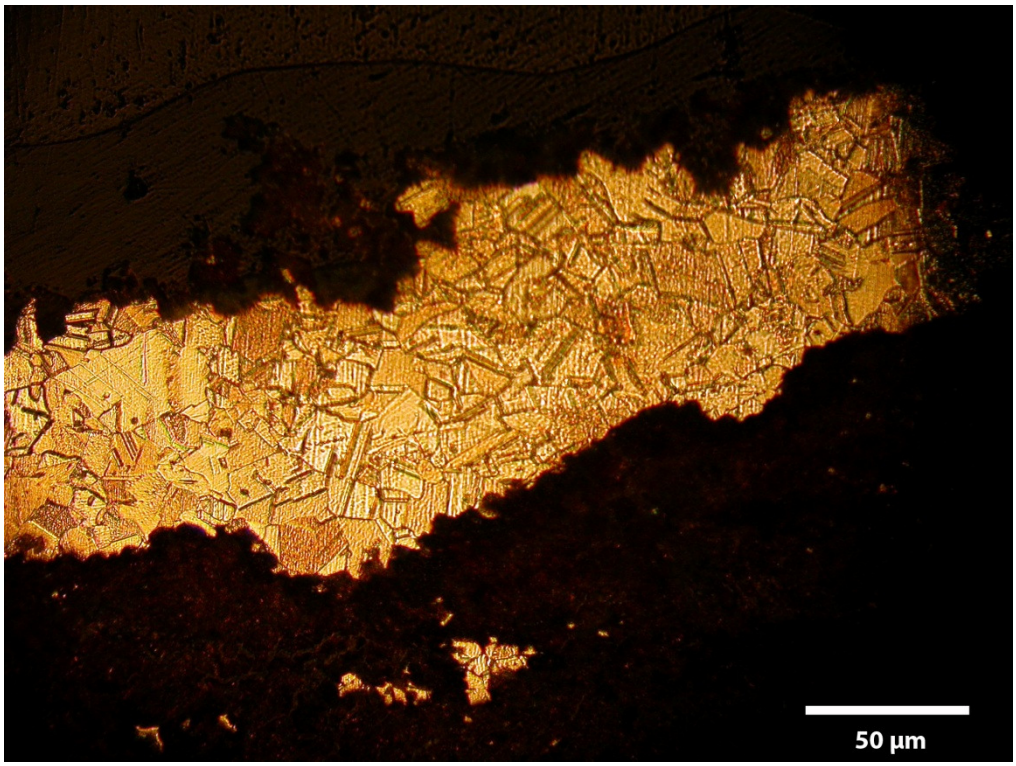

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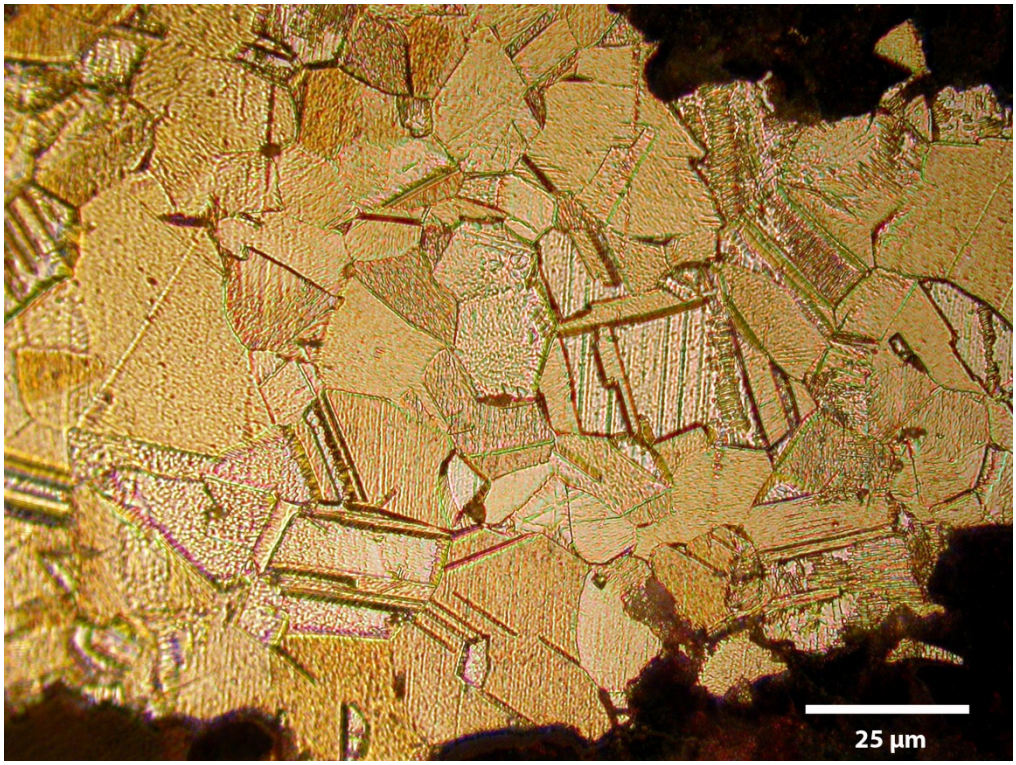

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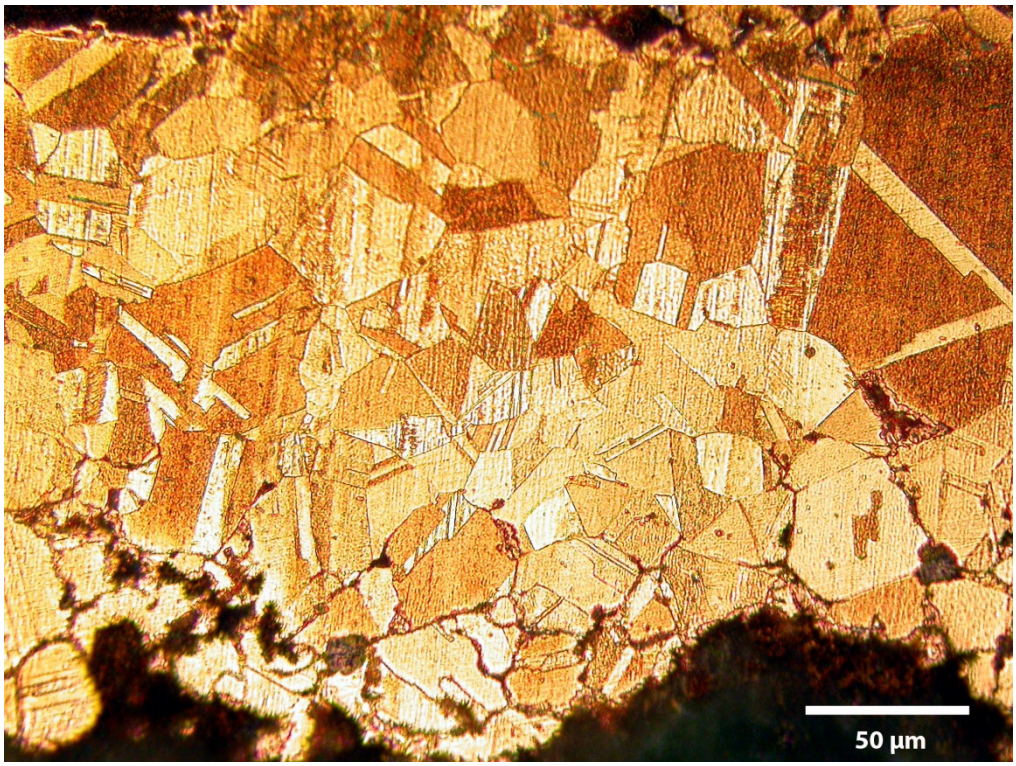
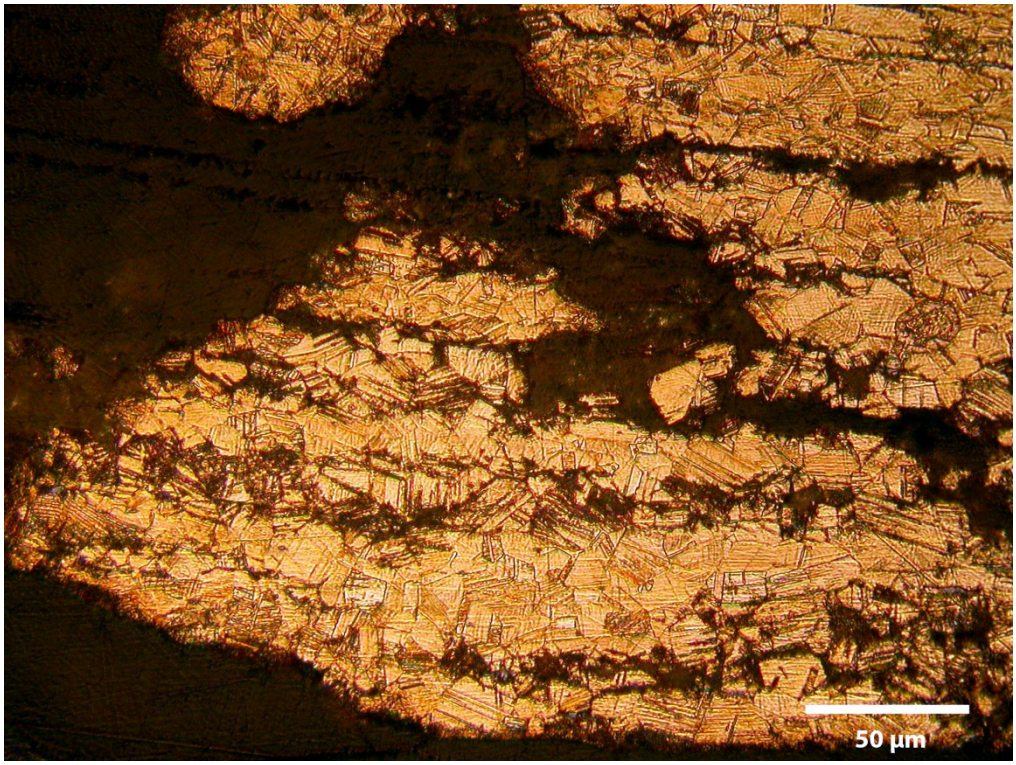


Figure A3.49 CHE701

Figure A3.50 CHE701



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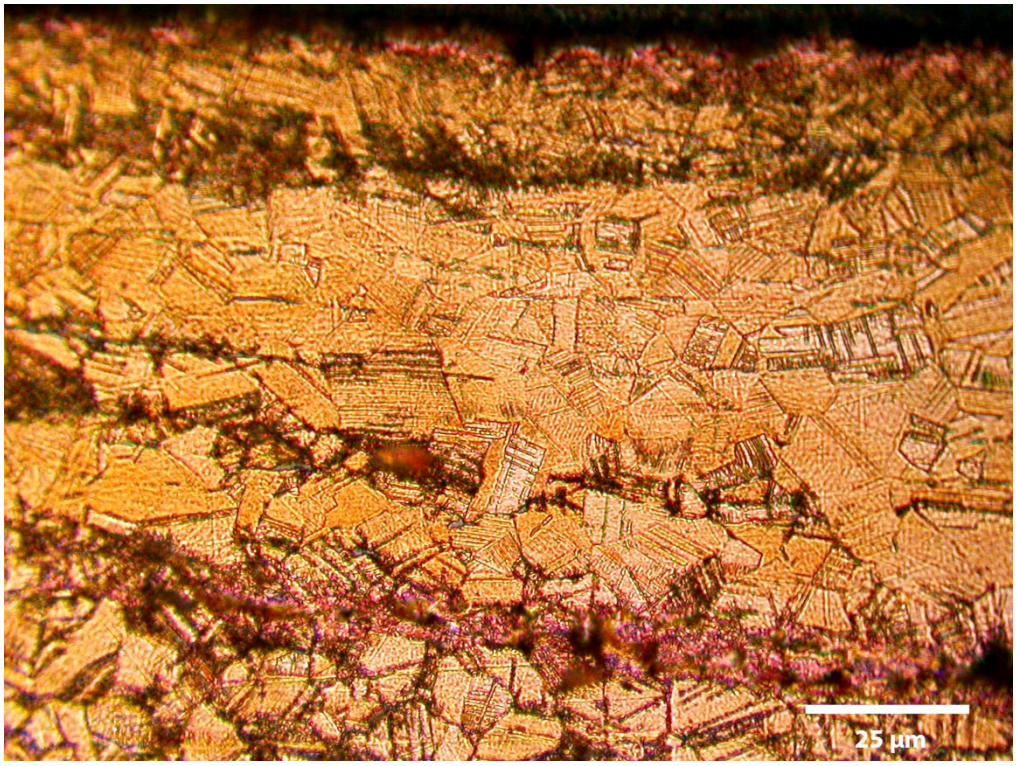

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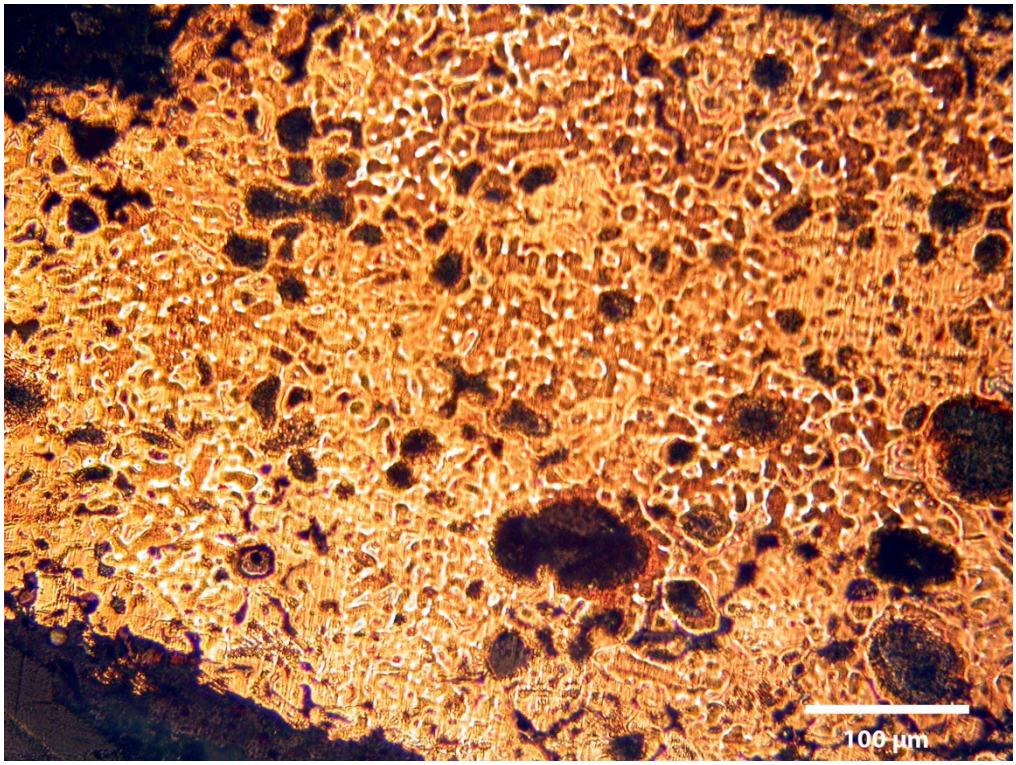

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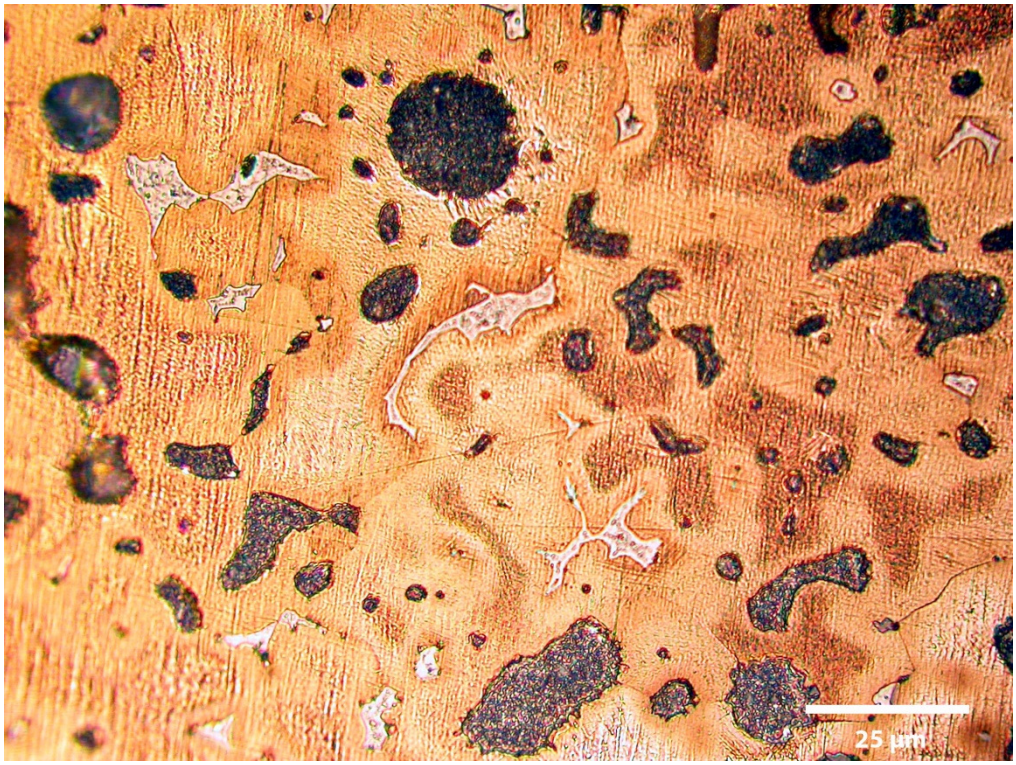

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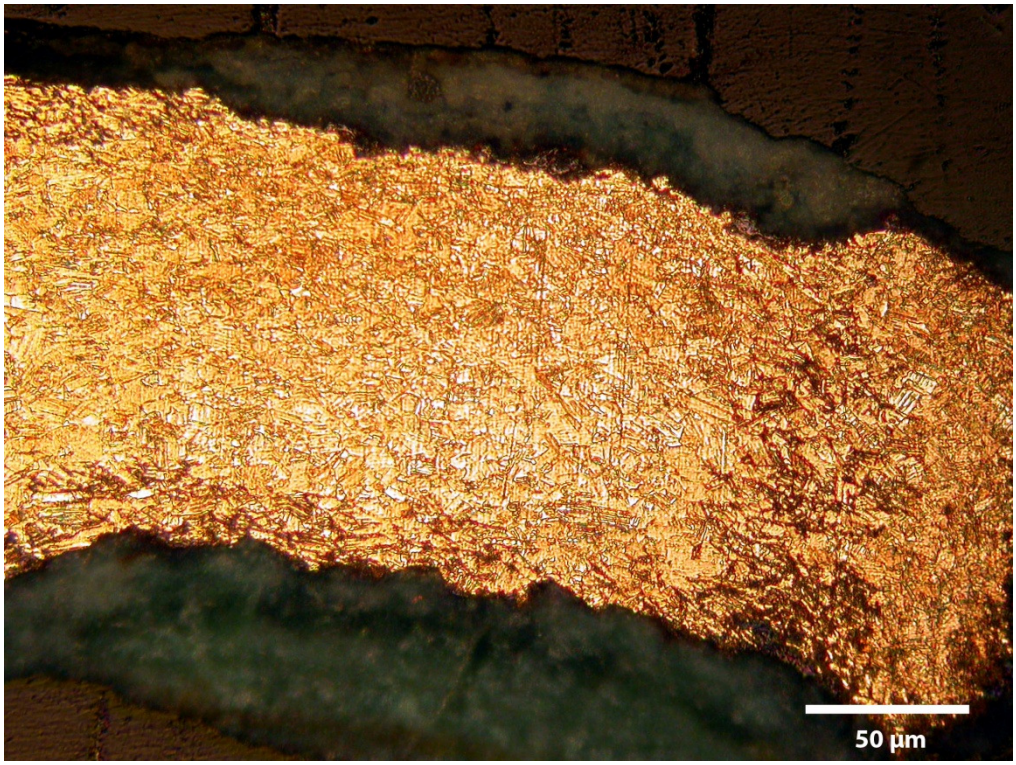

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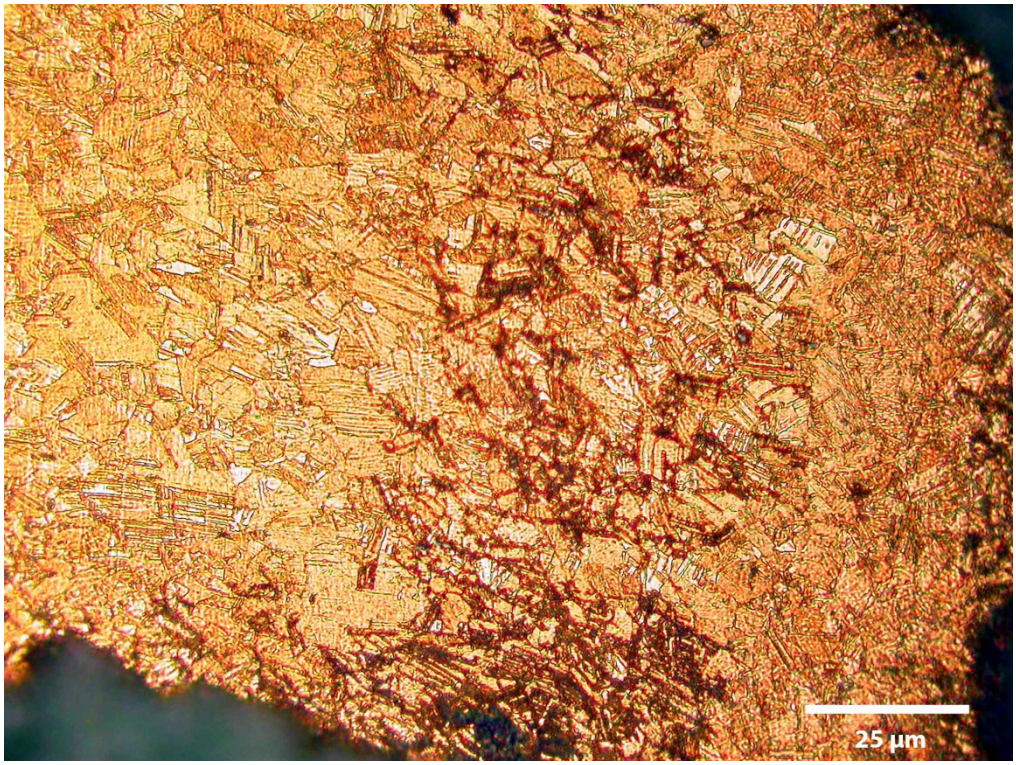

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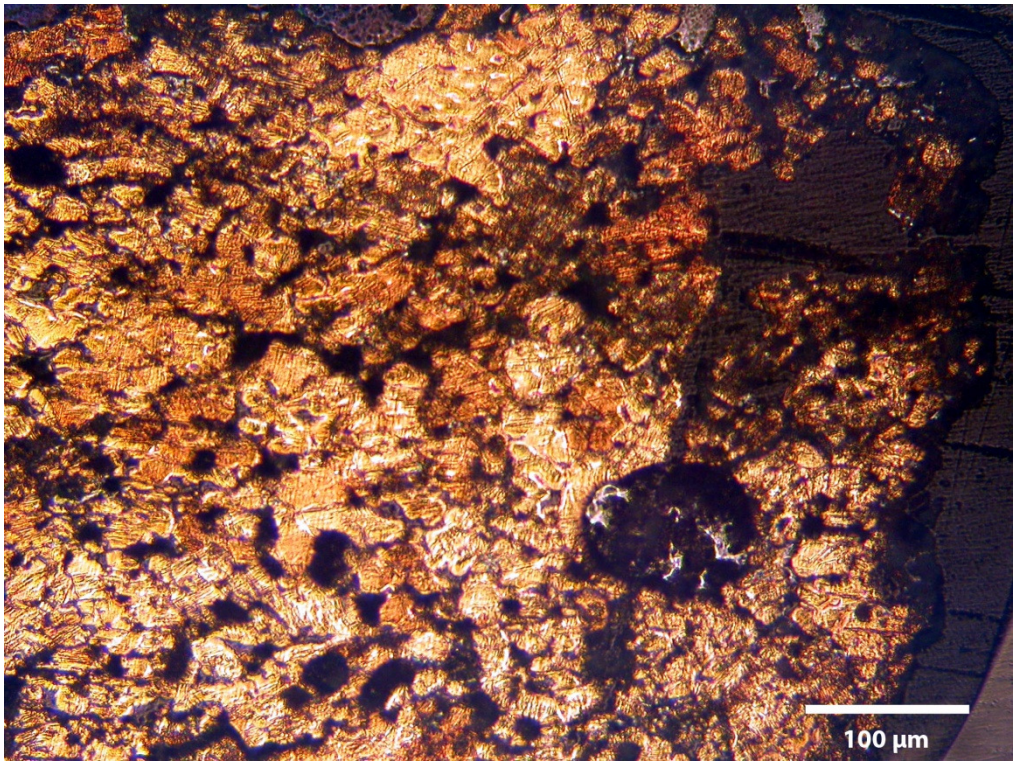
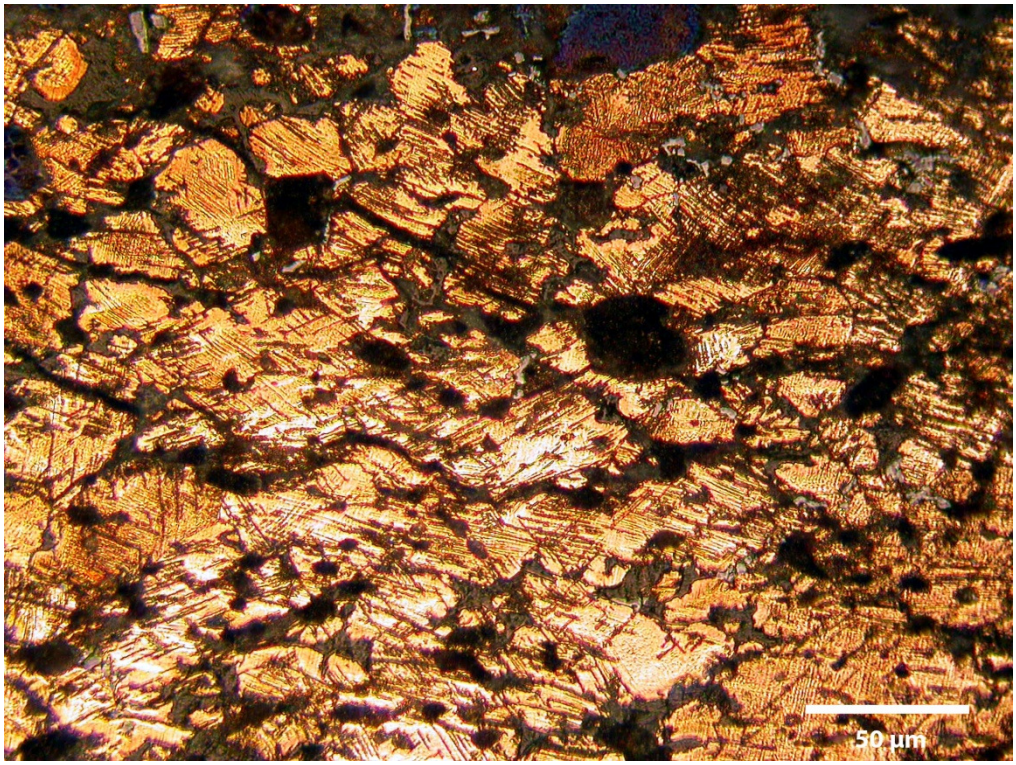


Figure A3.57 CHE1516



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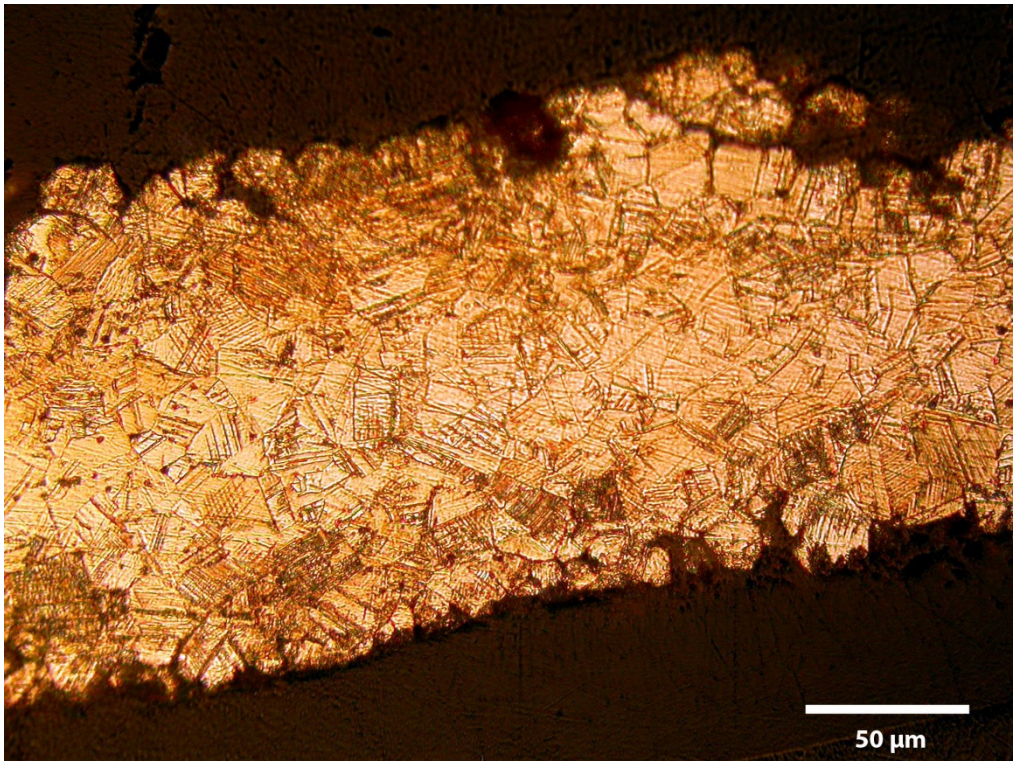
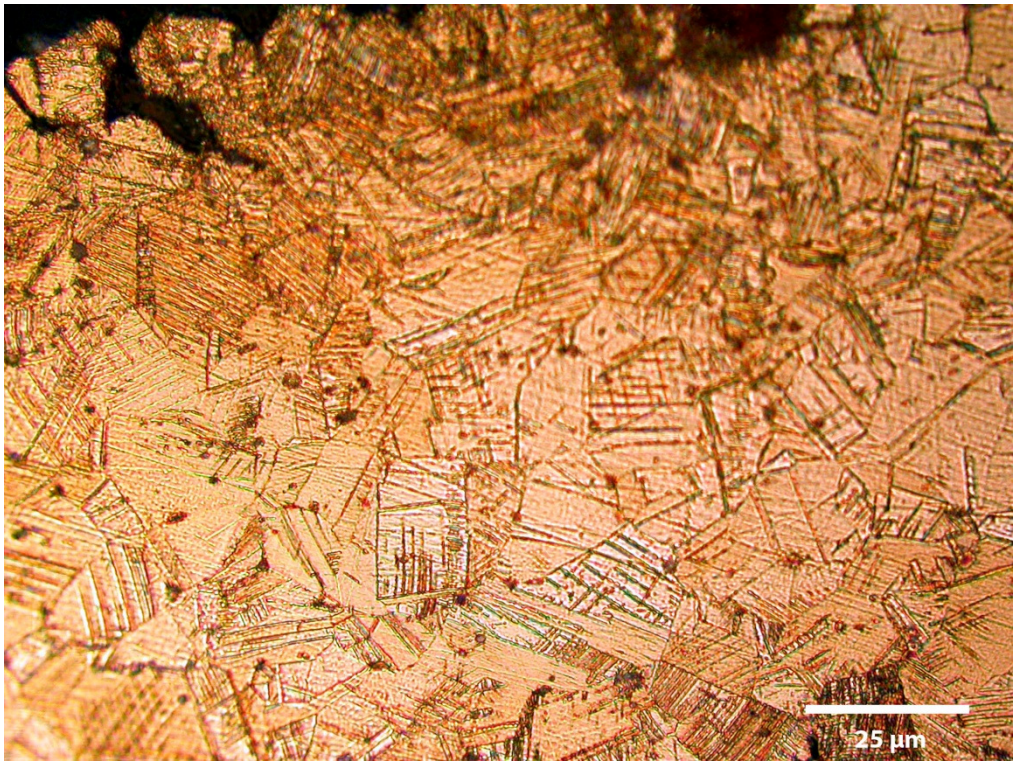


Figure A3.59 CHE1829



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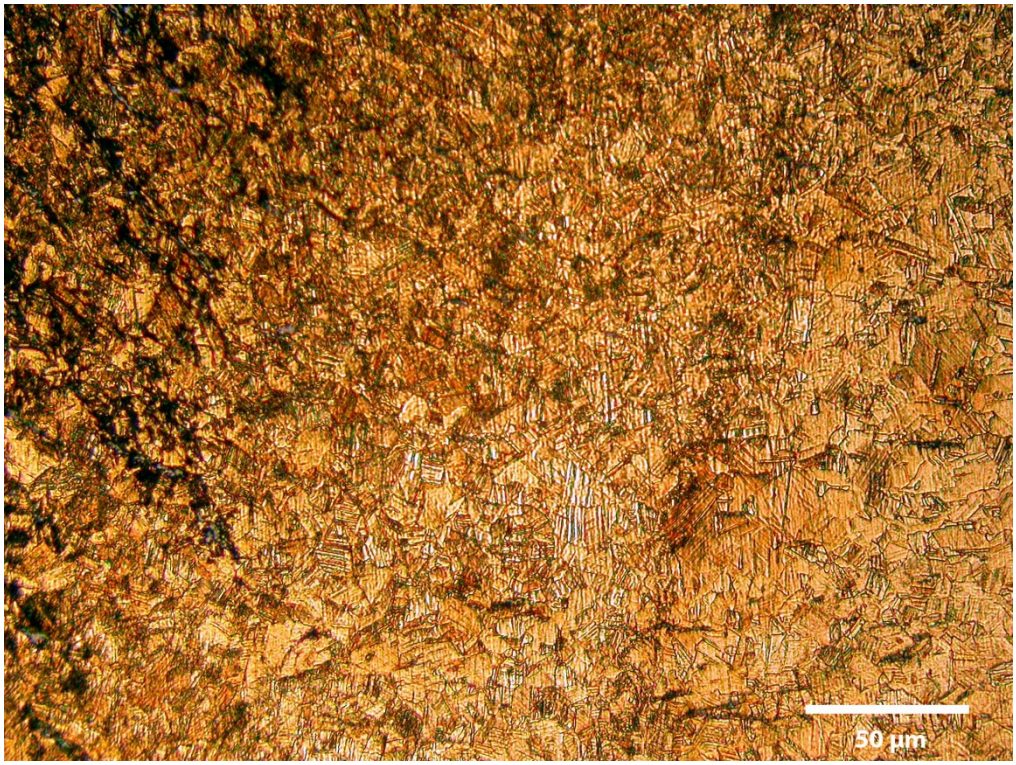
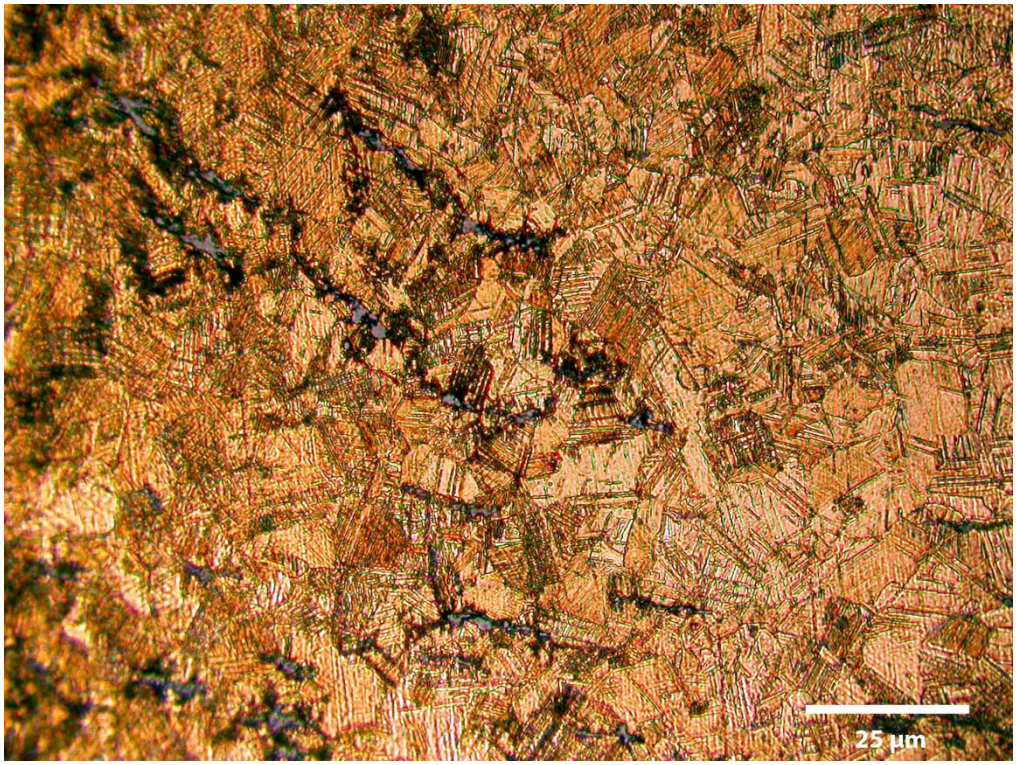


Figure A3.61 CHE1833



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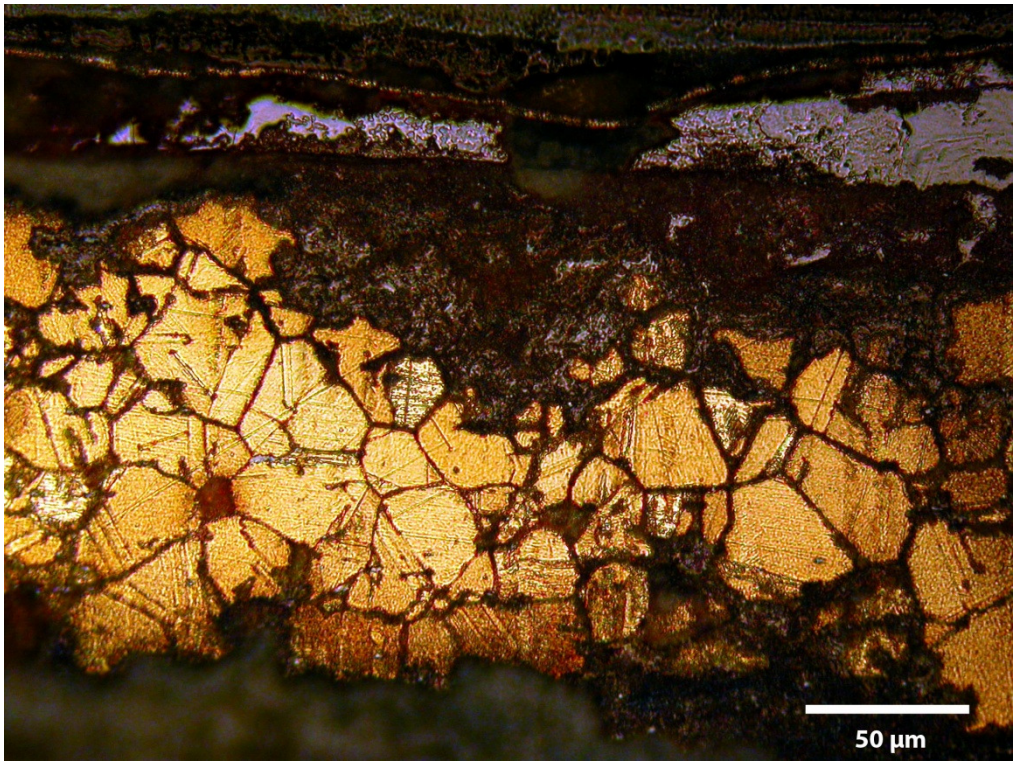
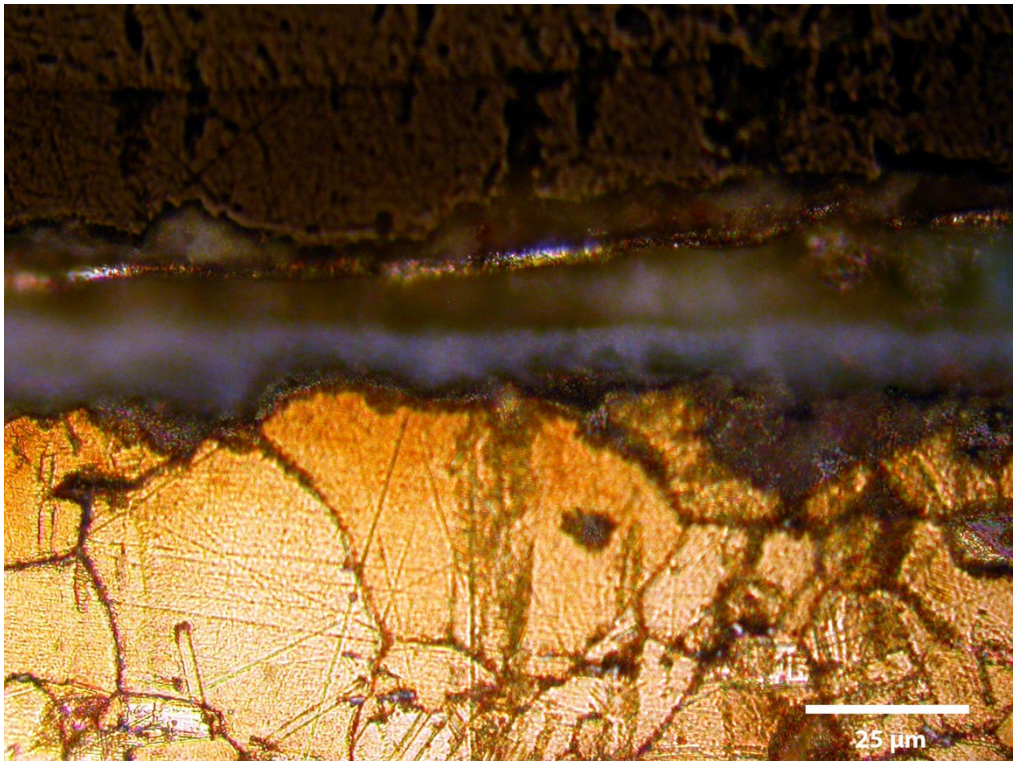


Figure A3.63 CHE1834



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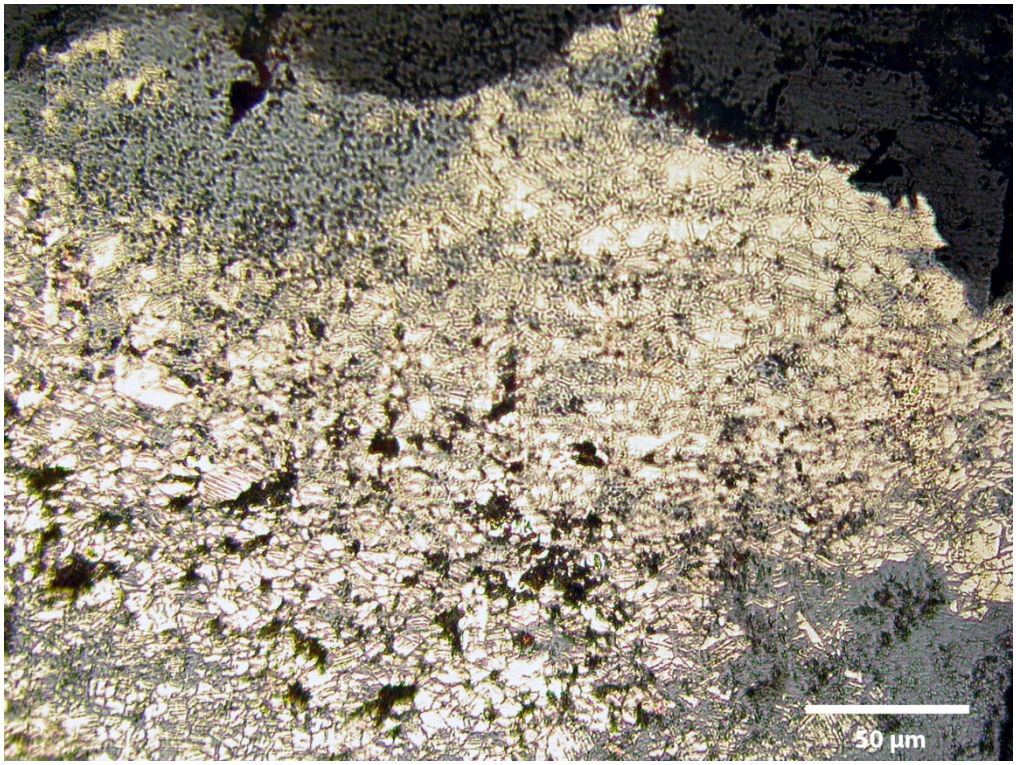

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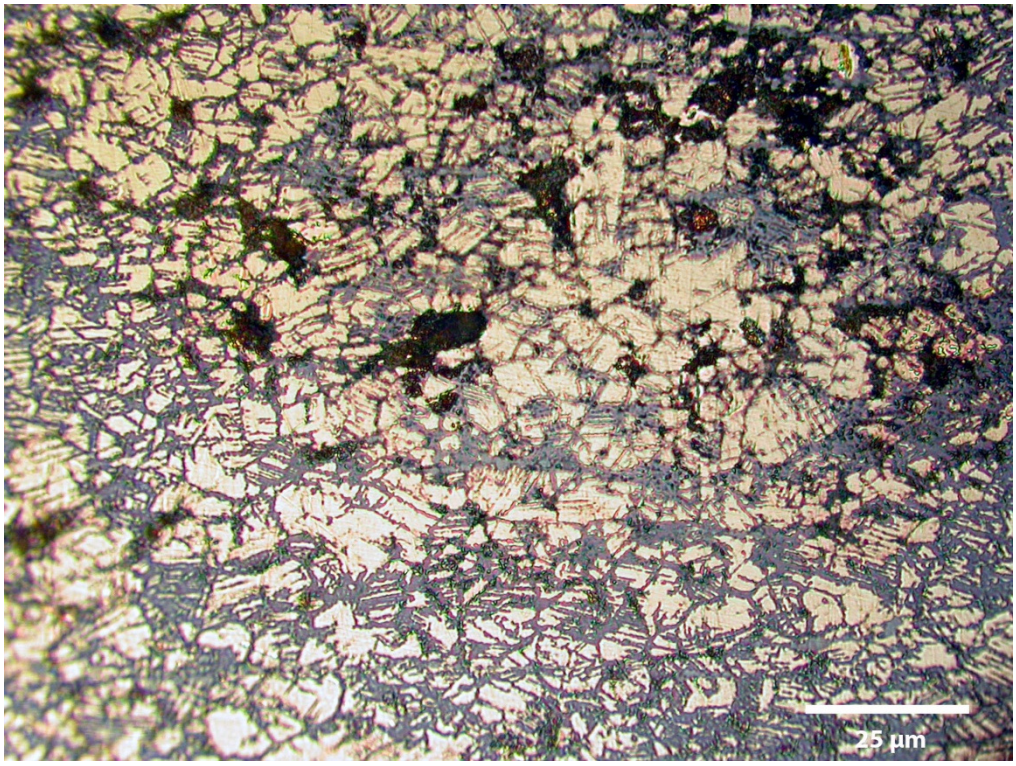

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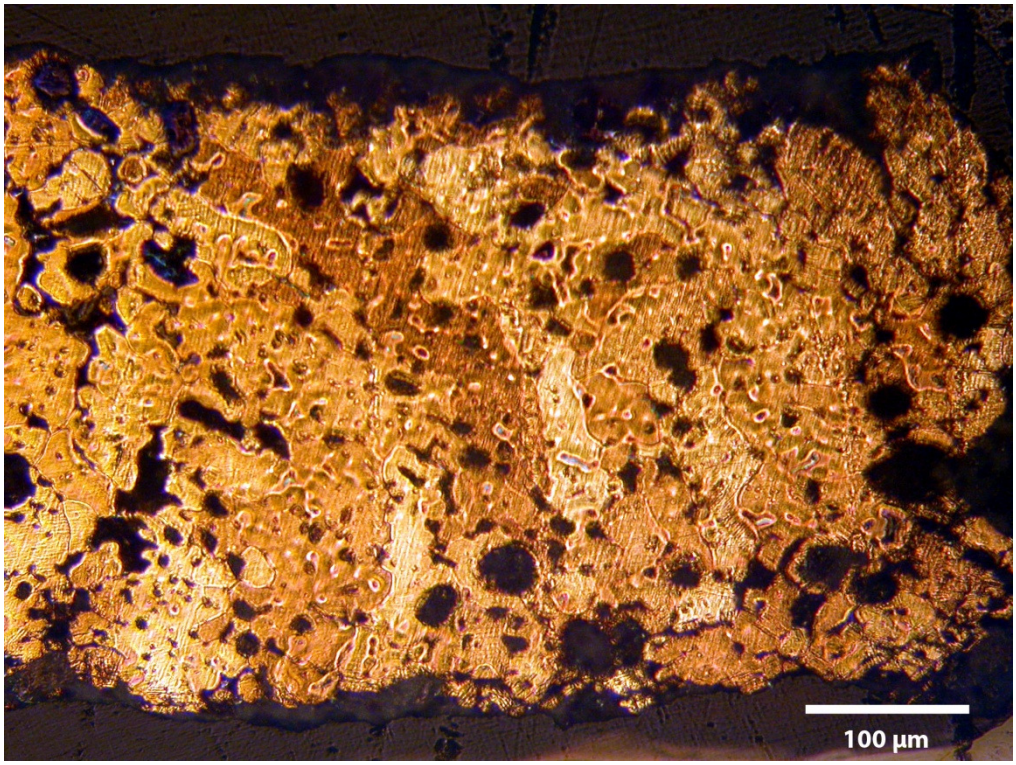


Figure A3.67 CHE1855

Figure A3.68 CHE1855

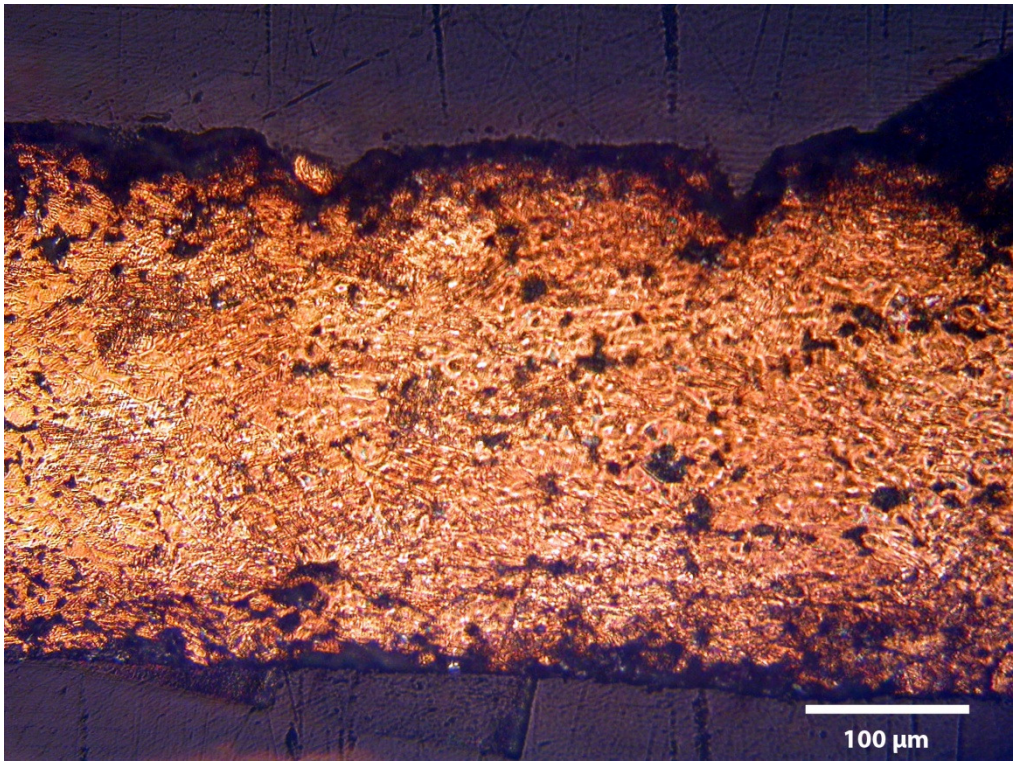


Figure A3.69 CHE2024

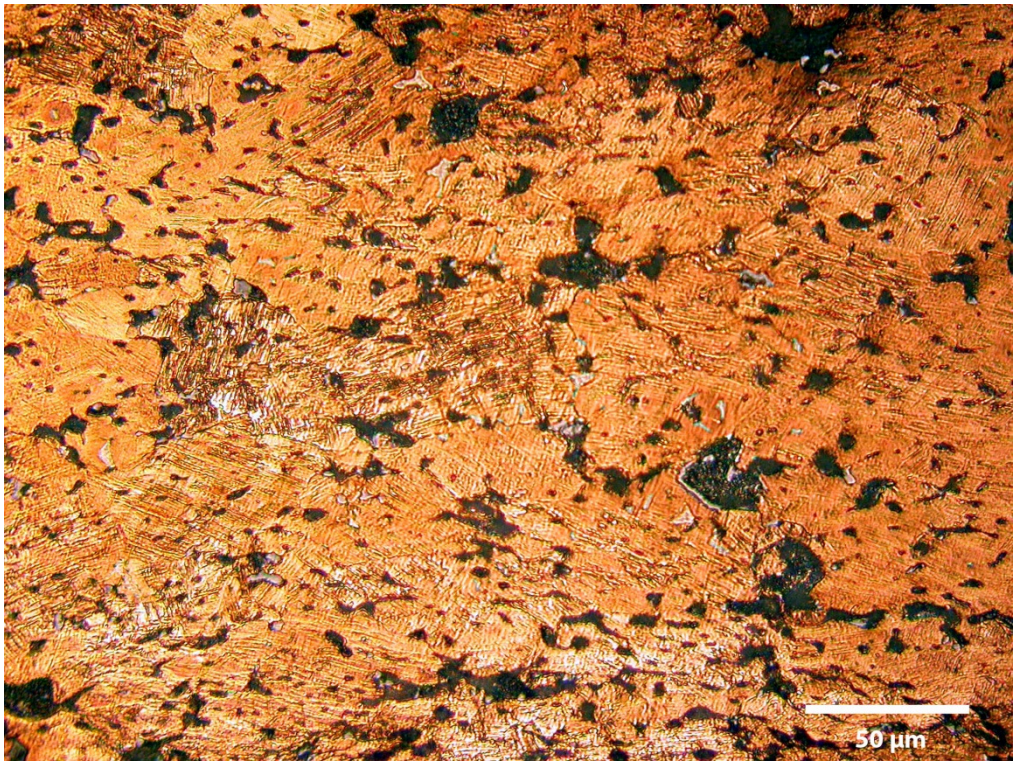
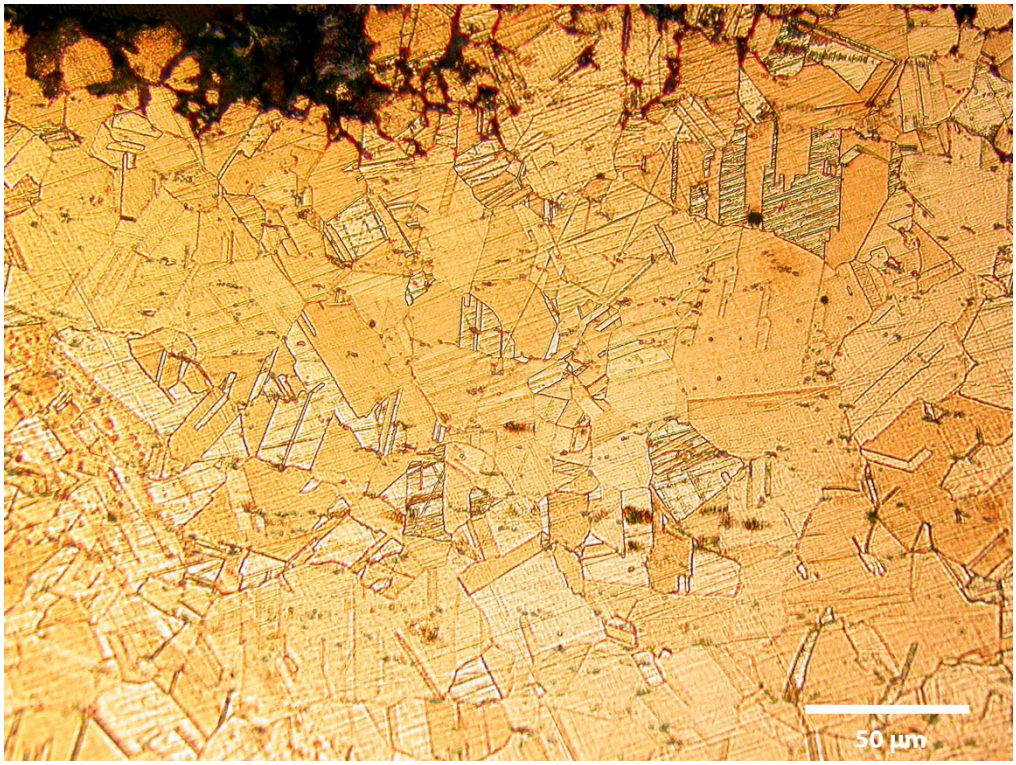


Figure A3.70 CHE2024



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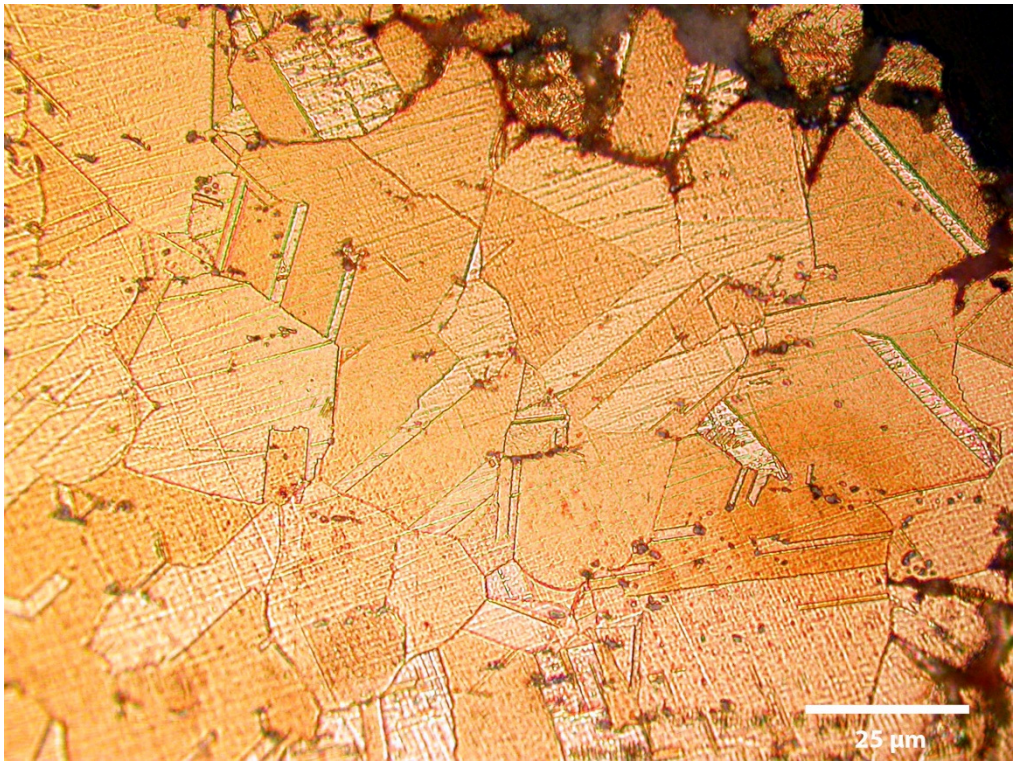

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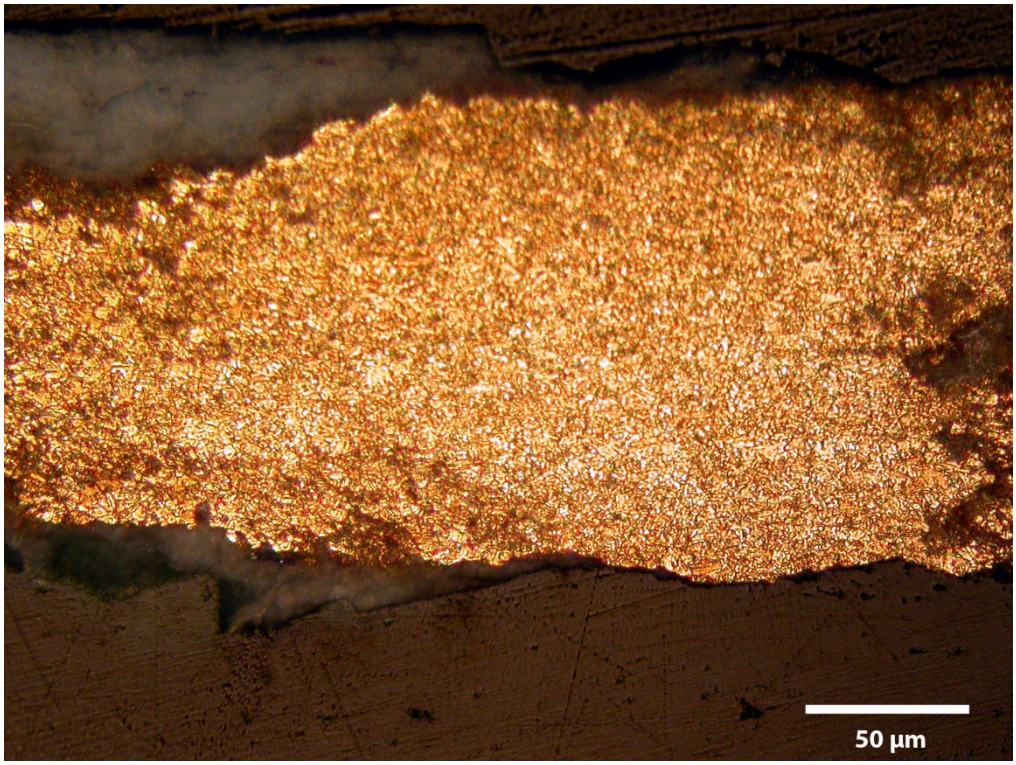

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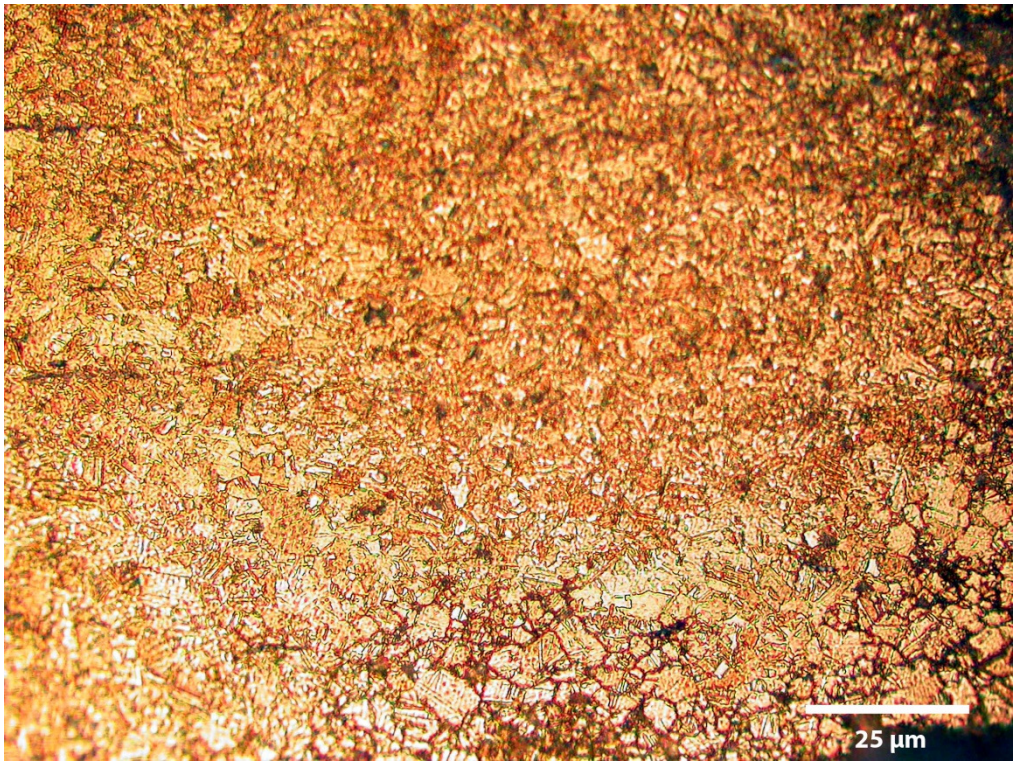

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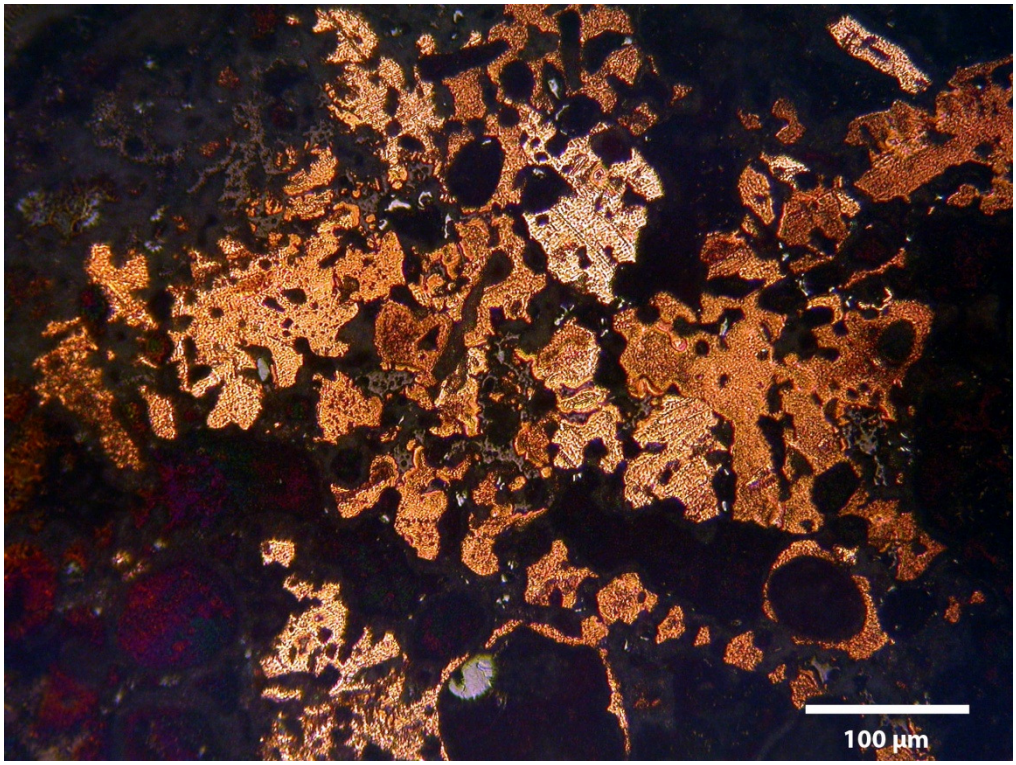

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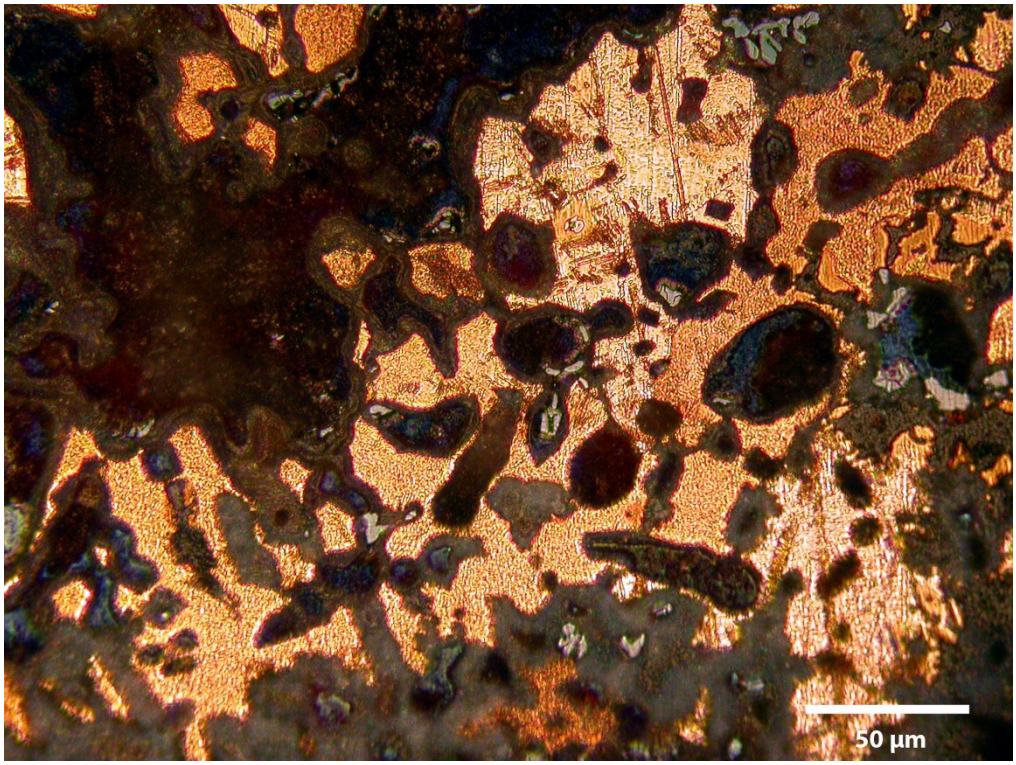

Figure A3.76 CHE8969

A3.6 Kingsholm

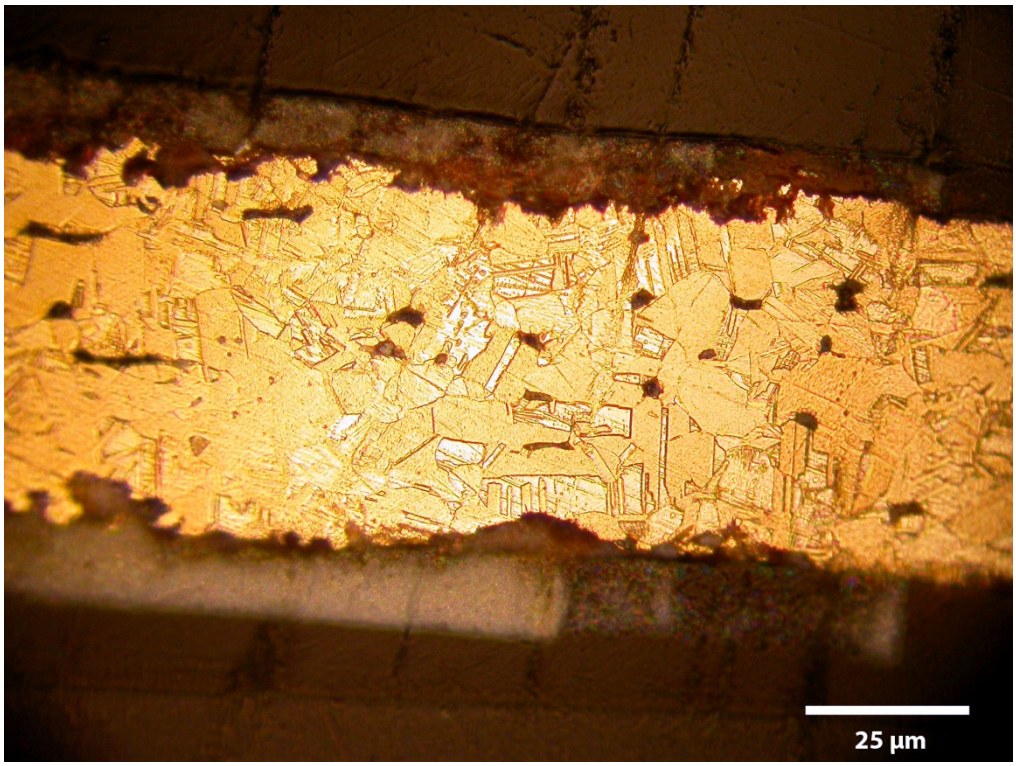

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Figure A3.78 GLC161

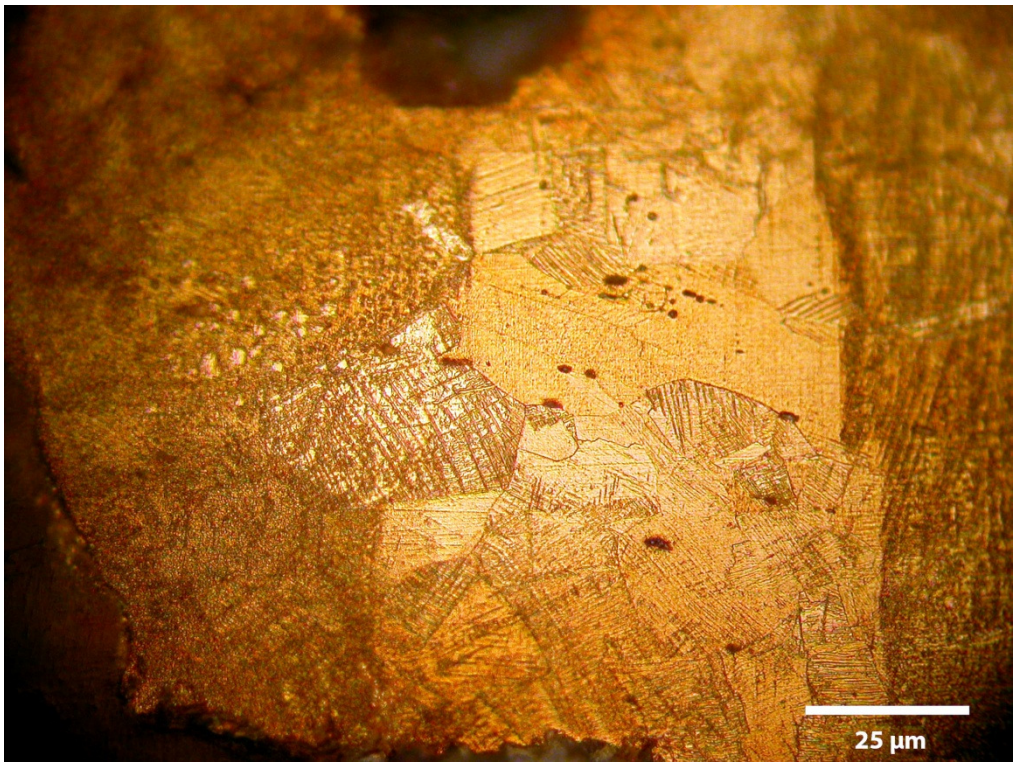

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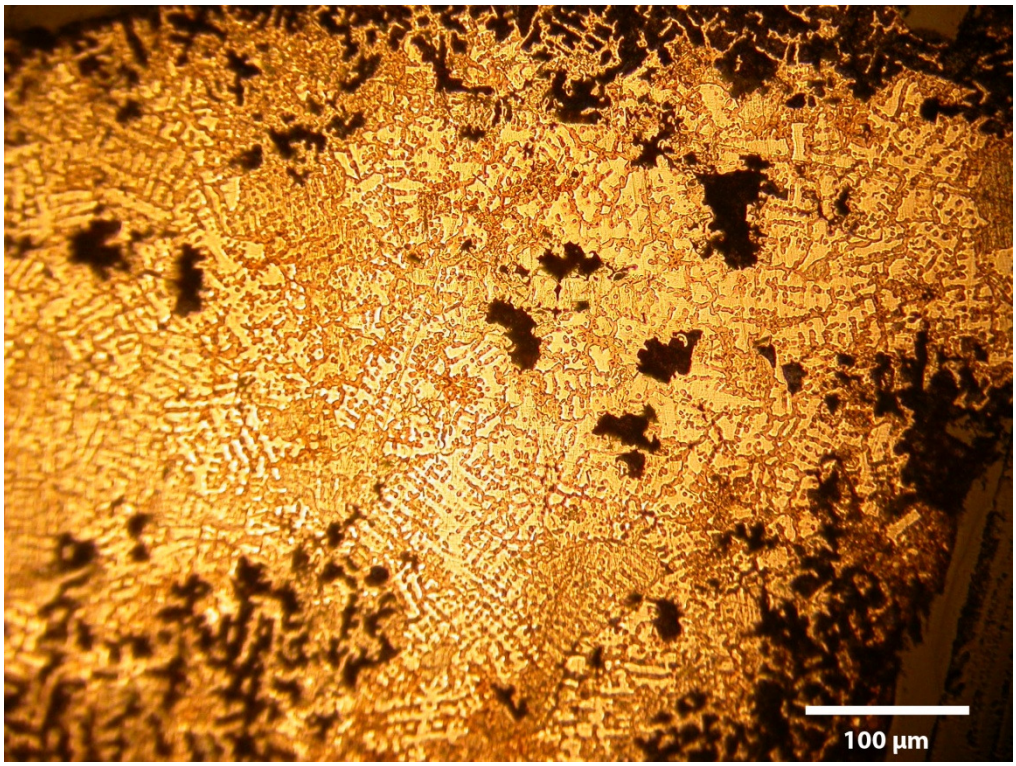
Figure A3.80 GLC442



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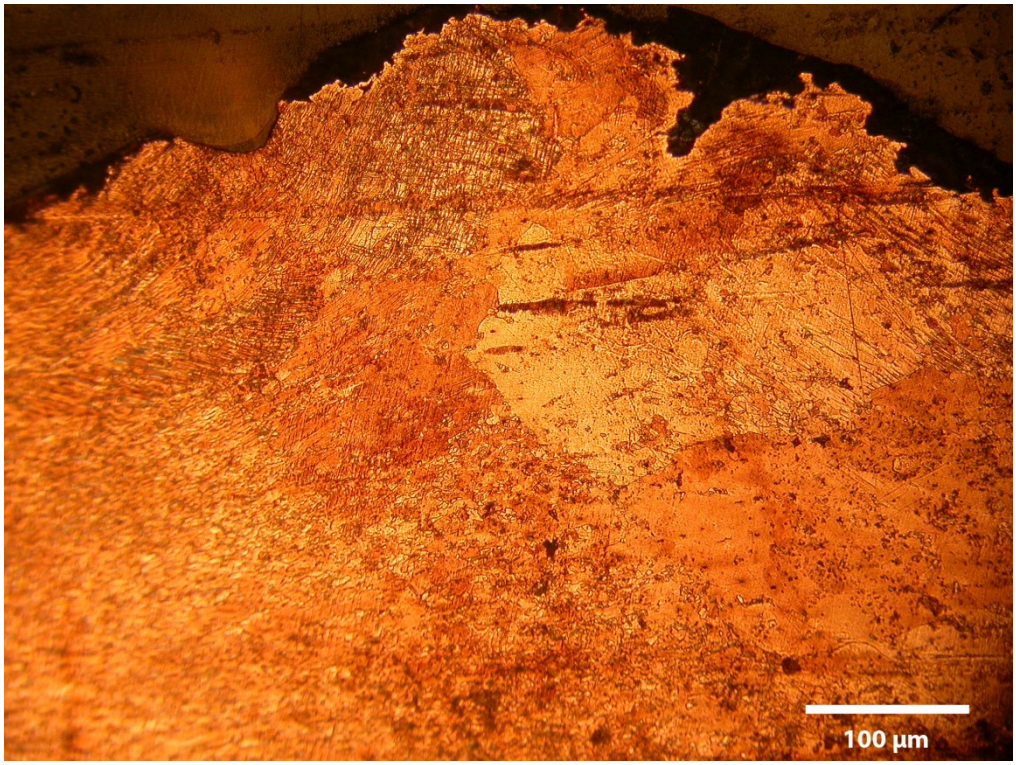

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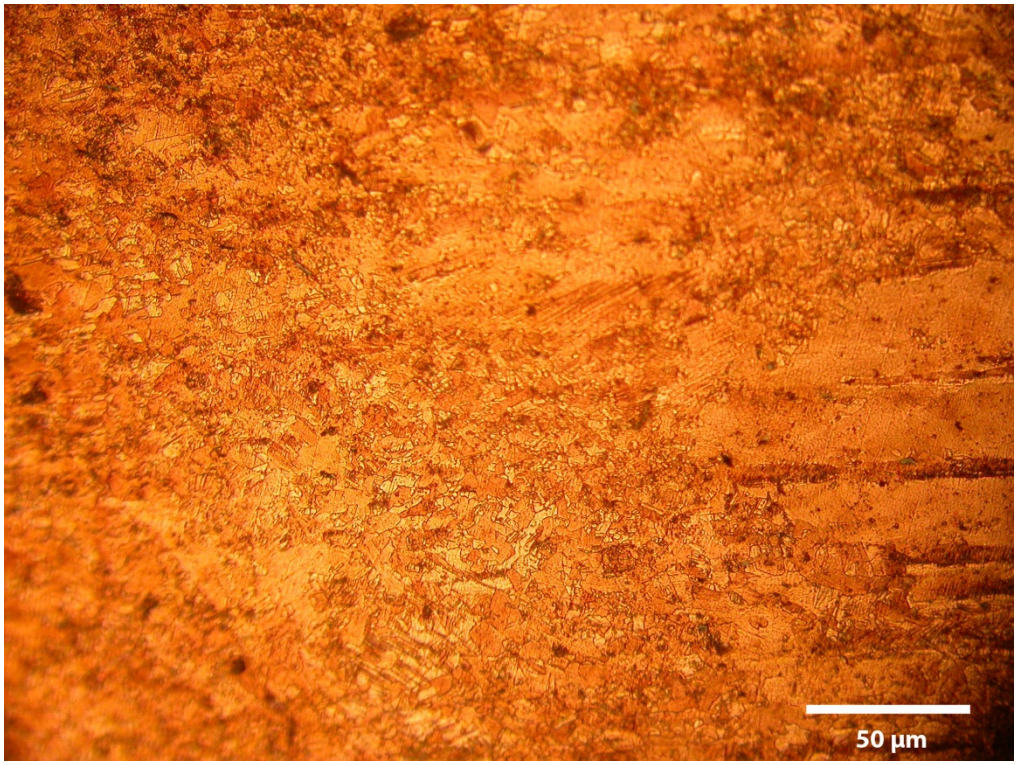

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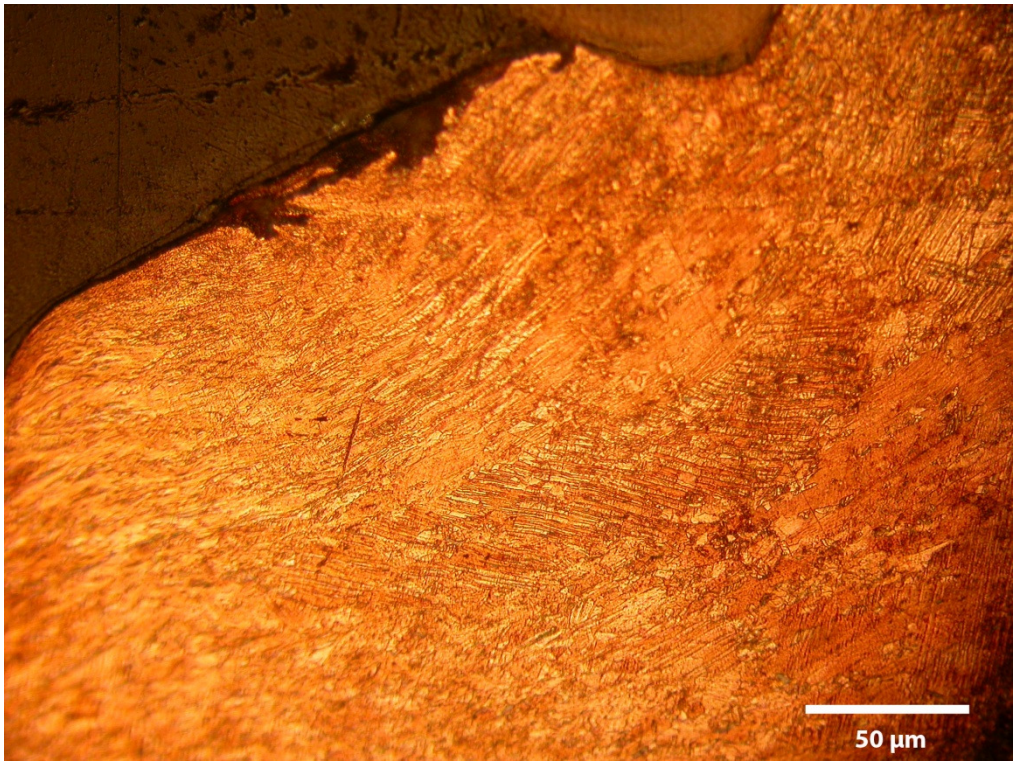
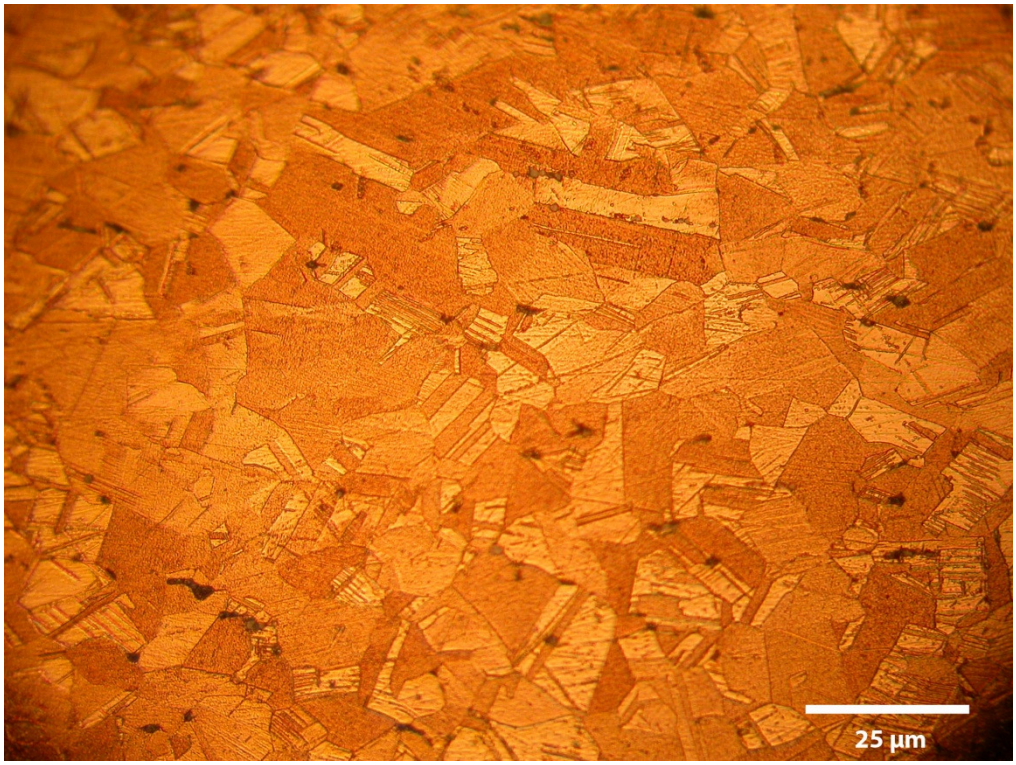


Figure A3.84 GLC813

Figure A3.85 GLC846

Figure A3.86 GLC1099



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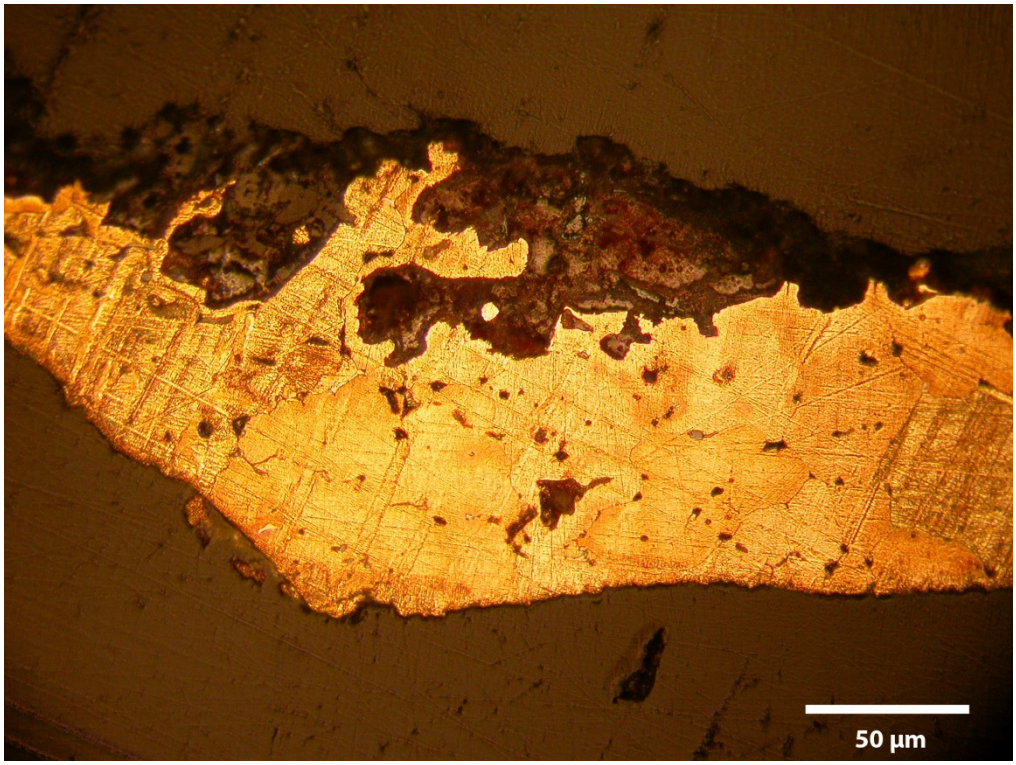

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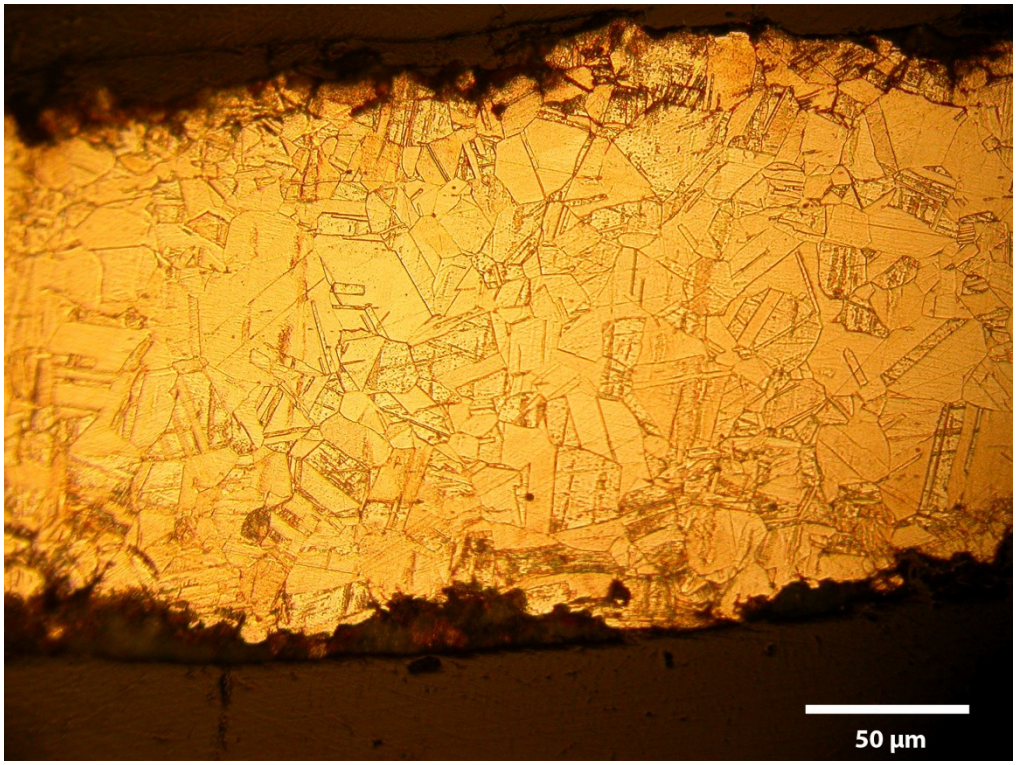
Figure A3.89 GLC1176



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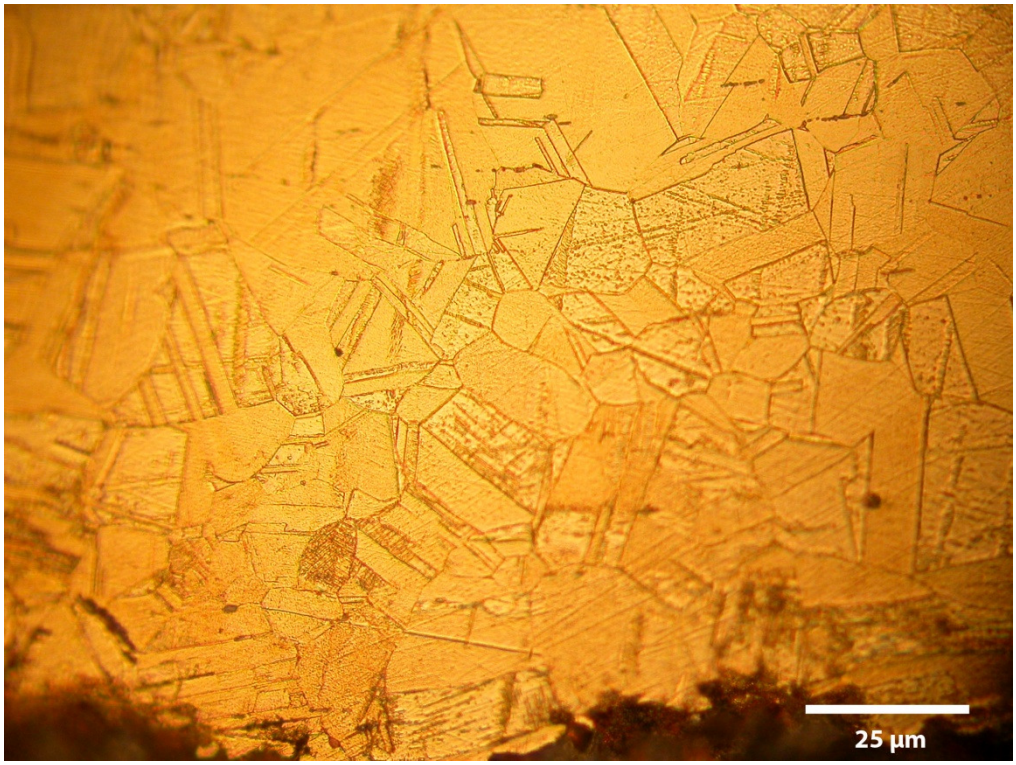

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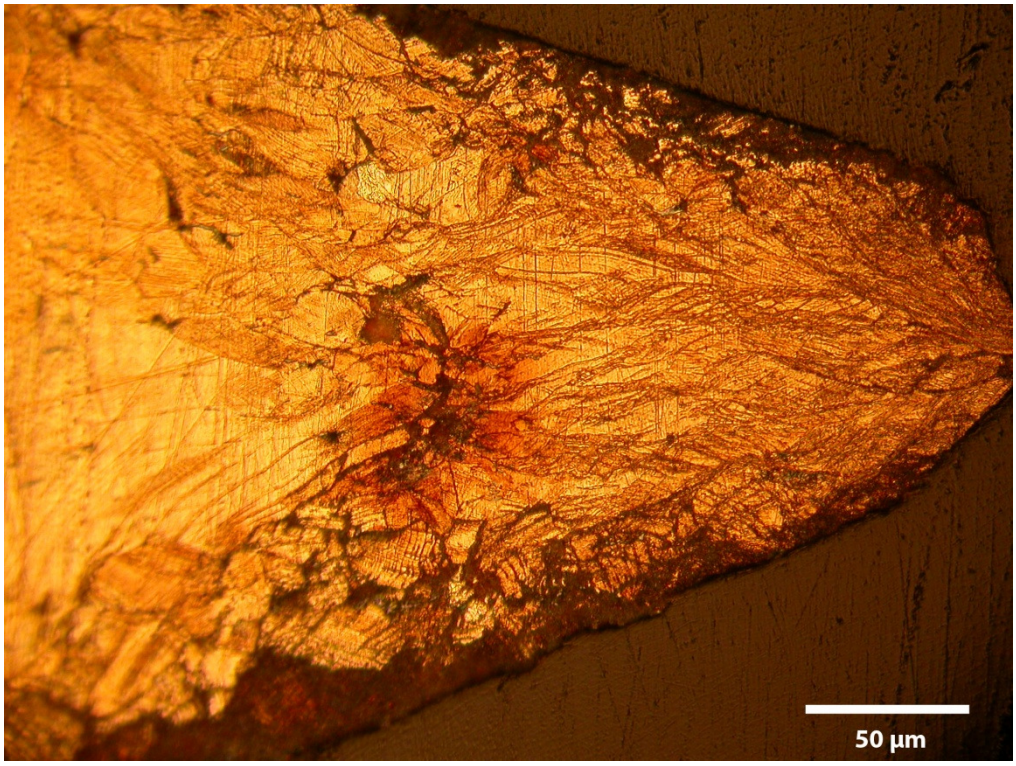

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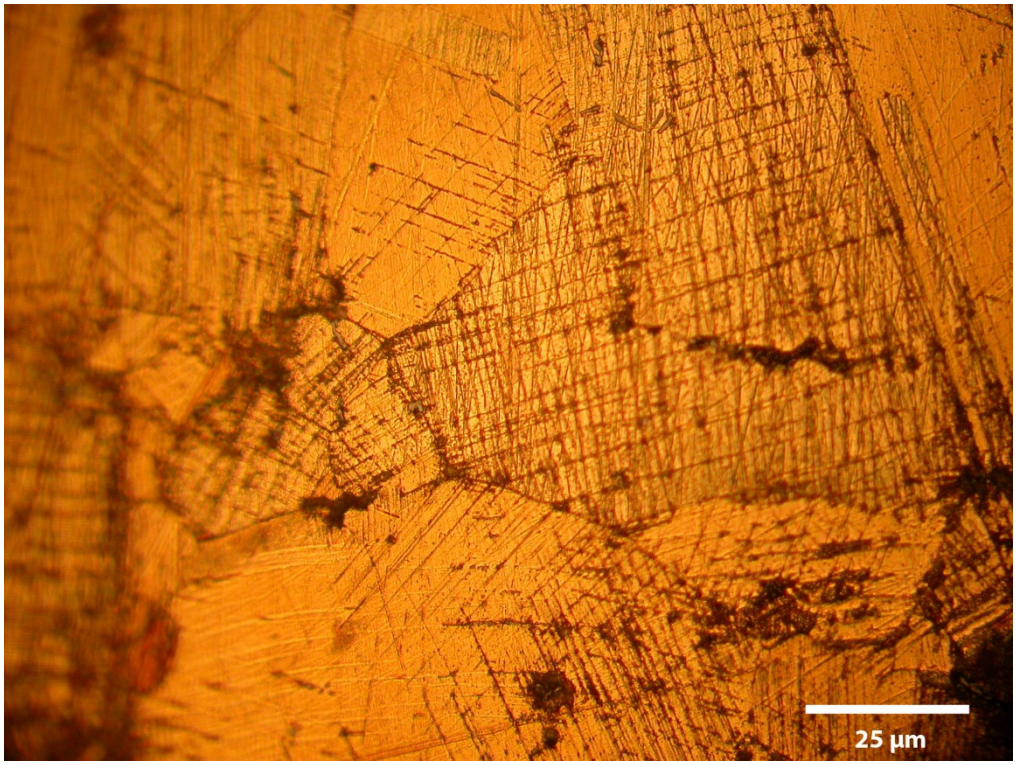

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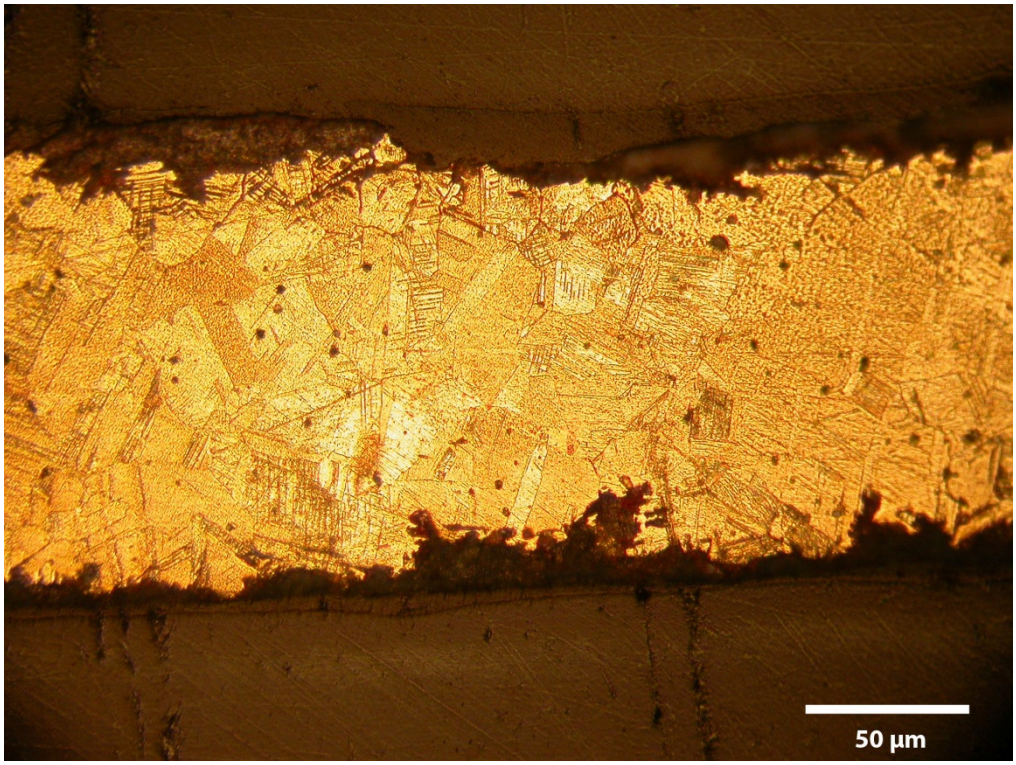

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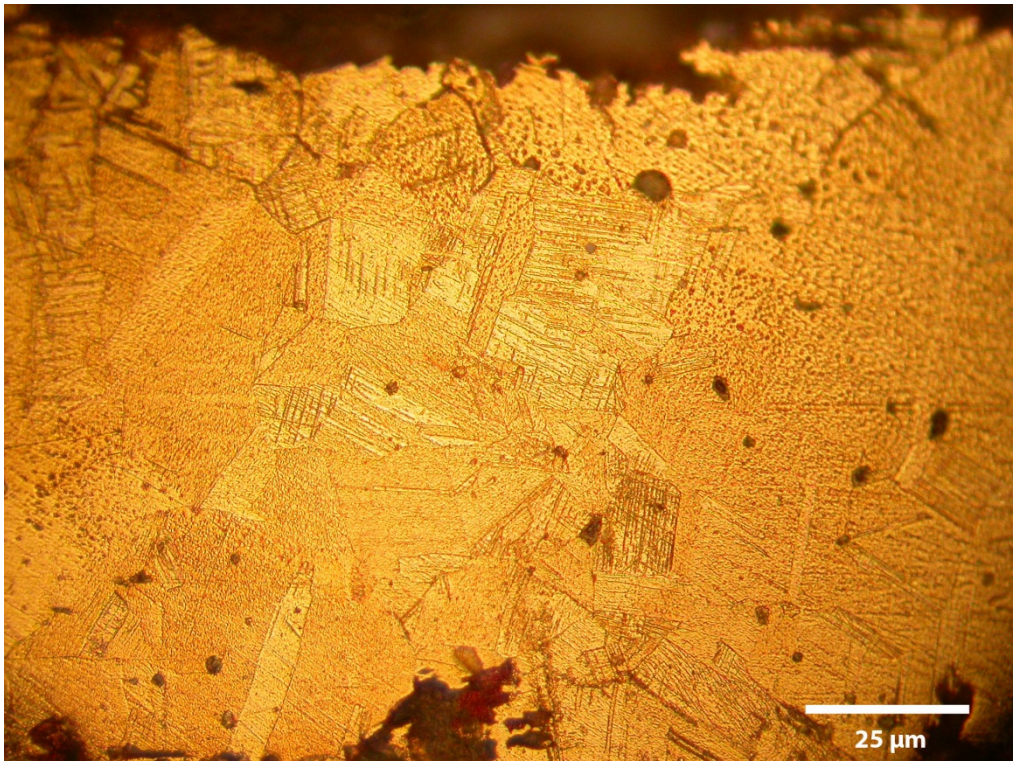

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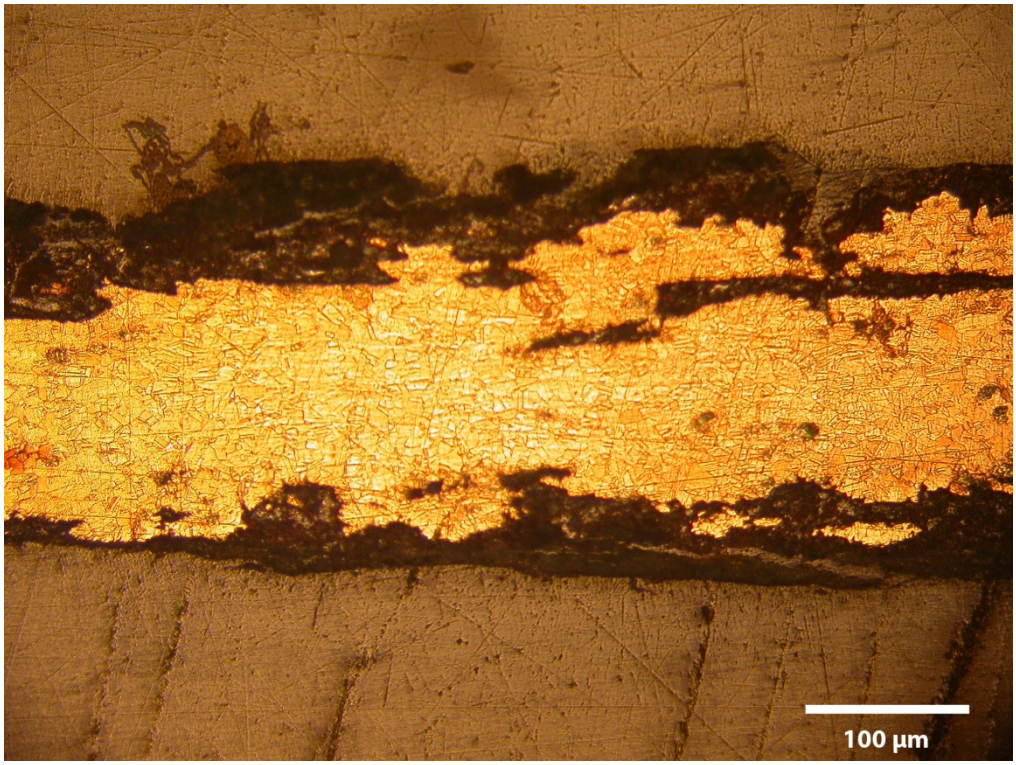

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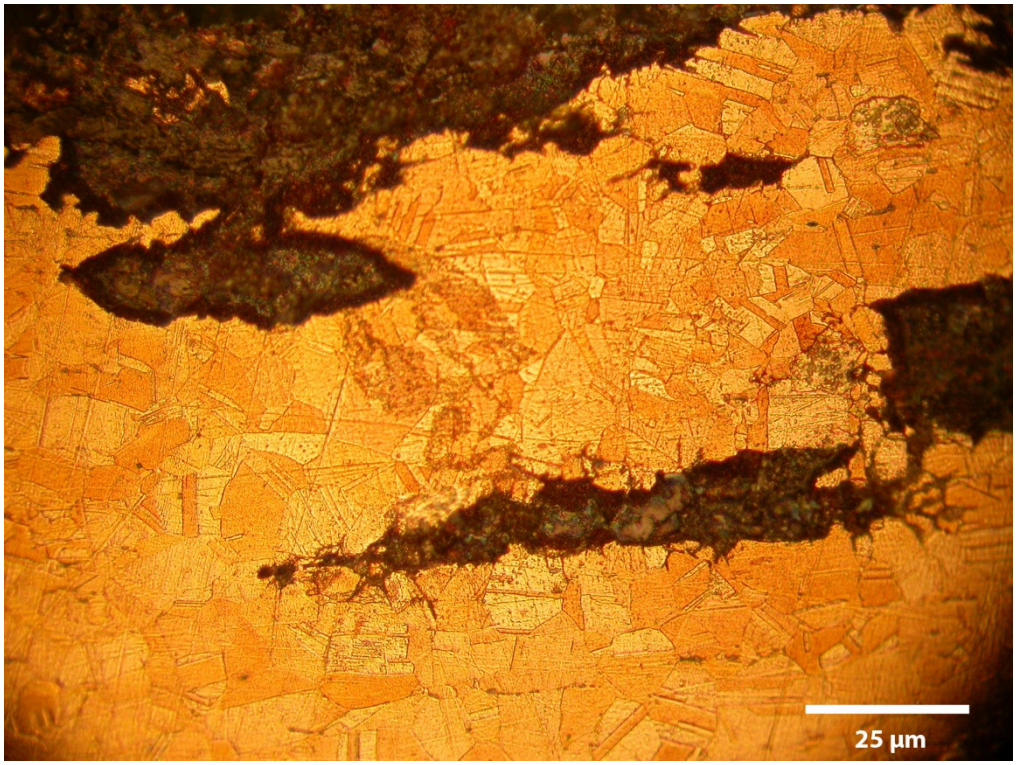

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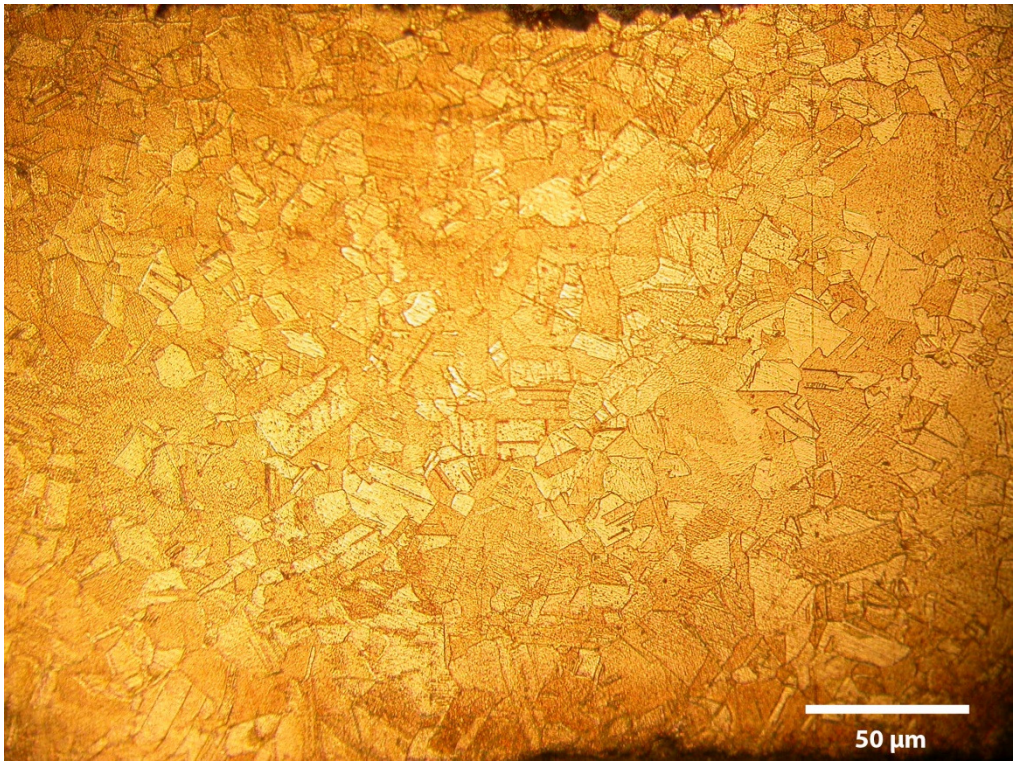

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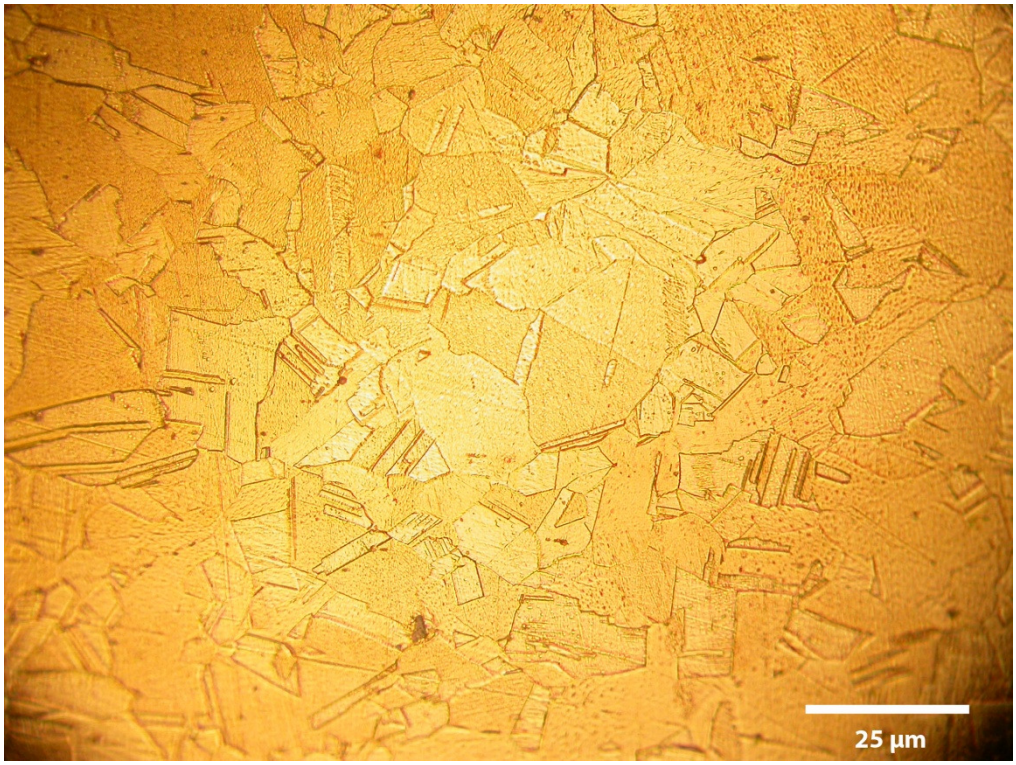

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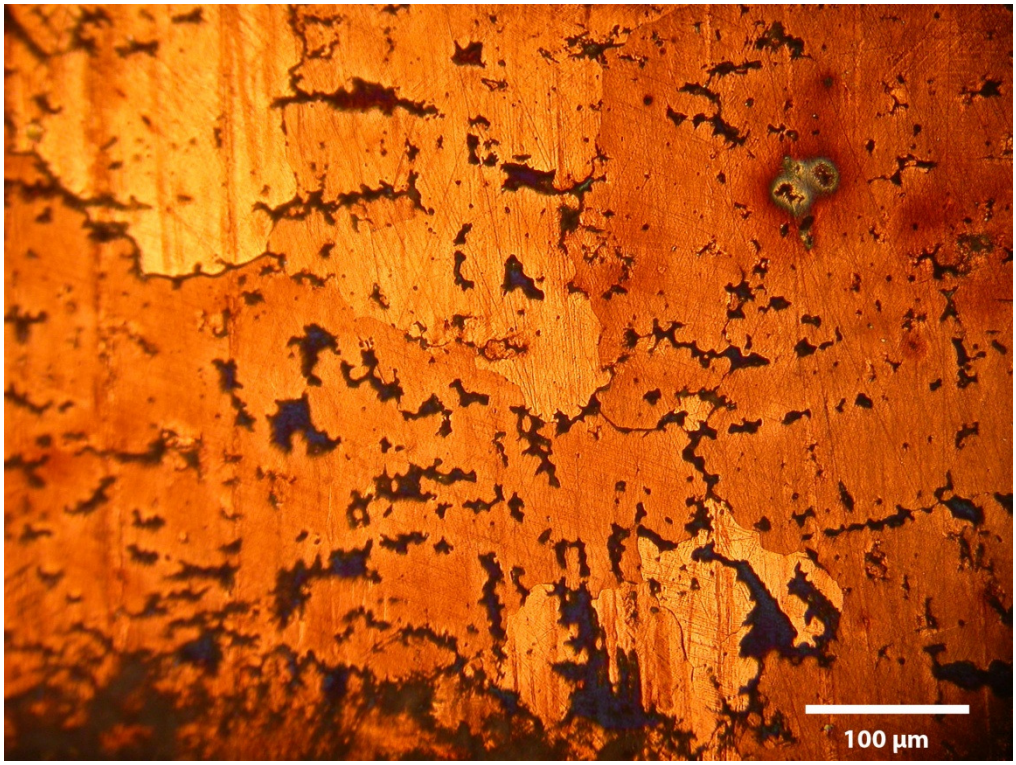

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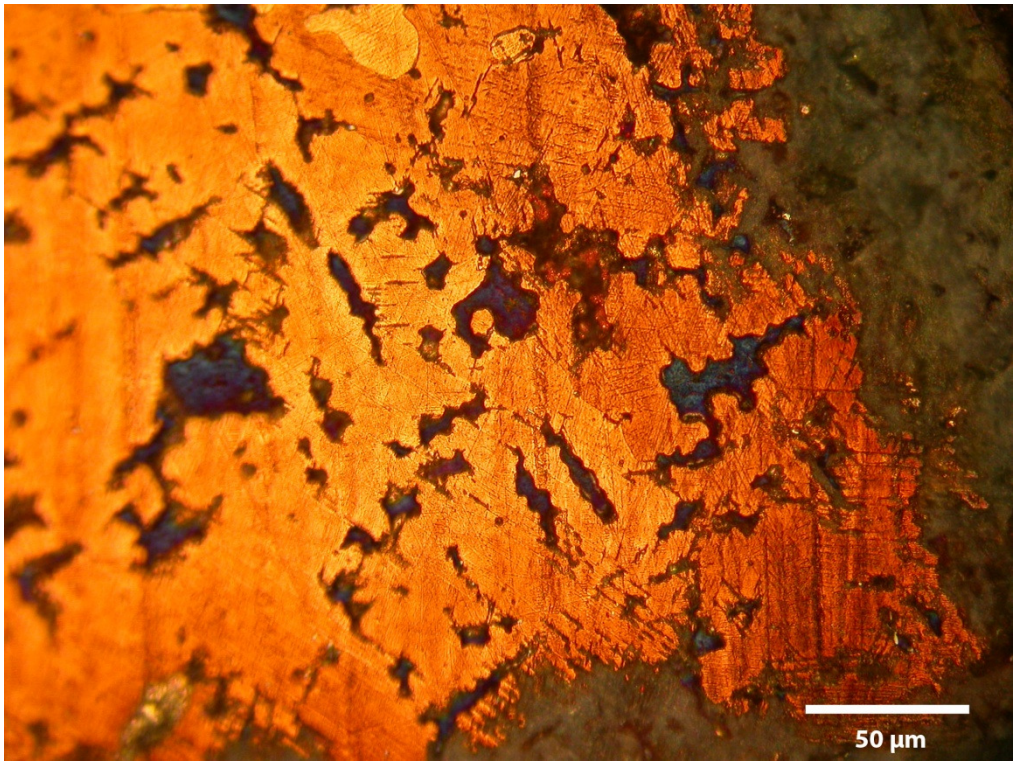

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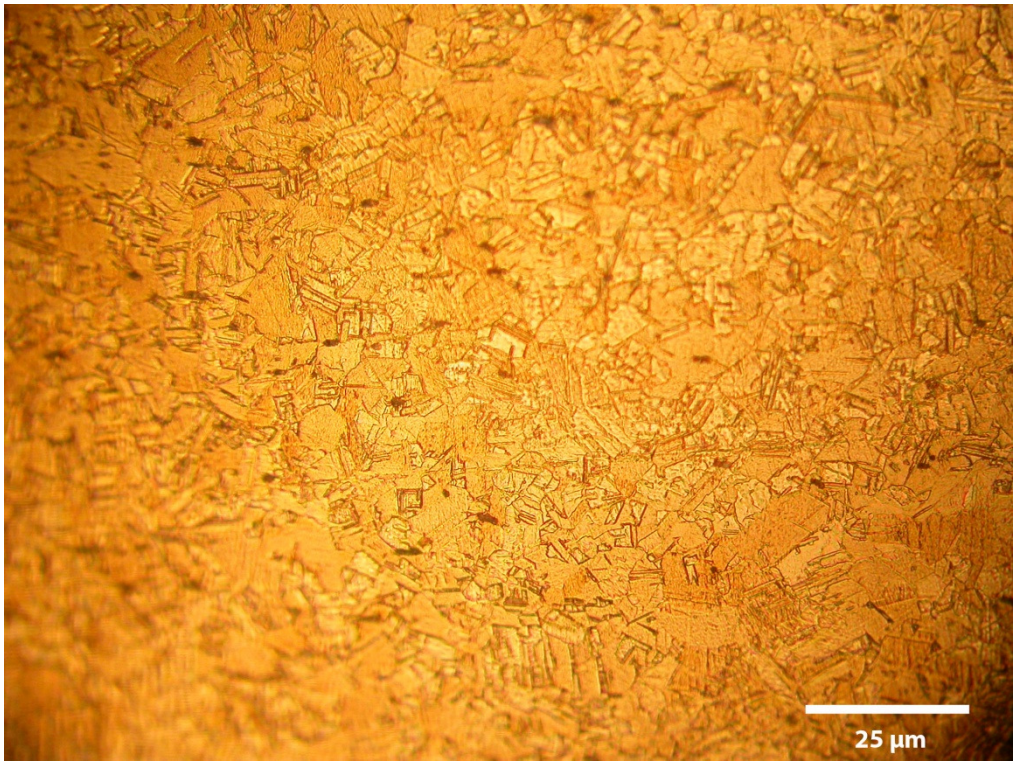
Figure A3.102 GLC1685



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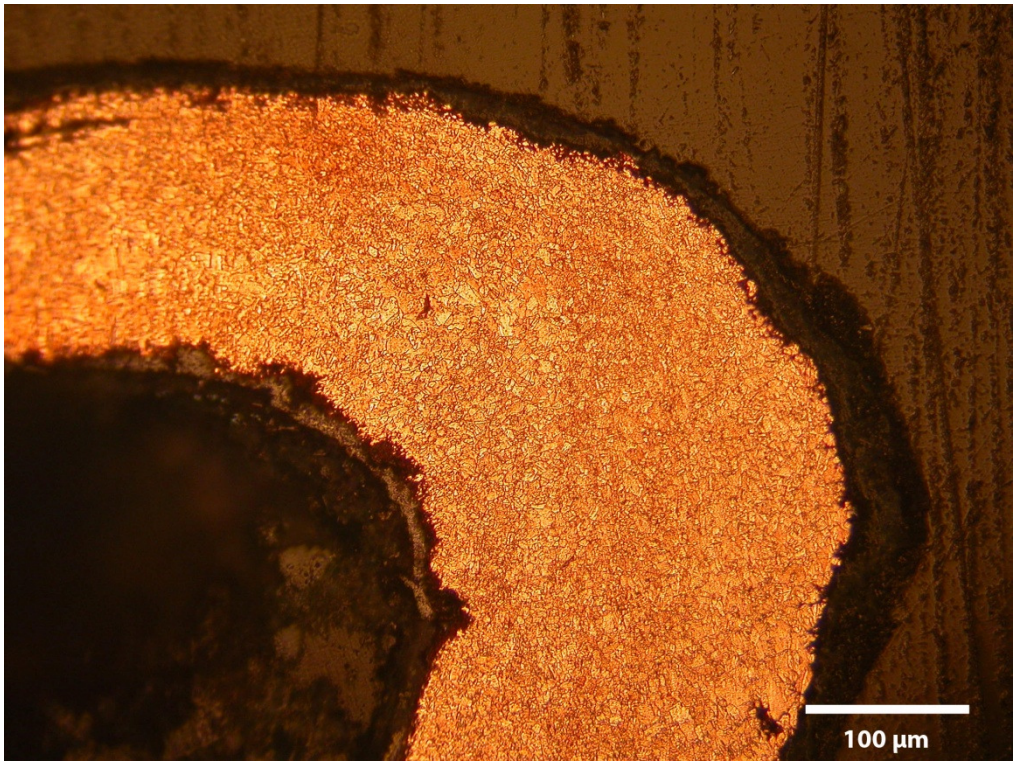

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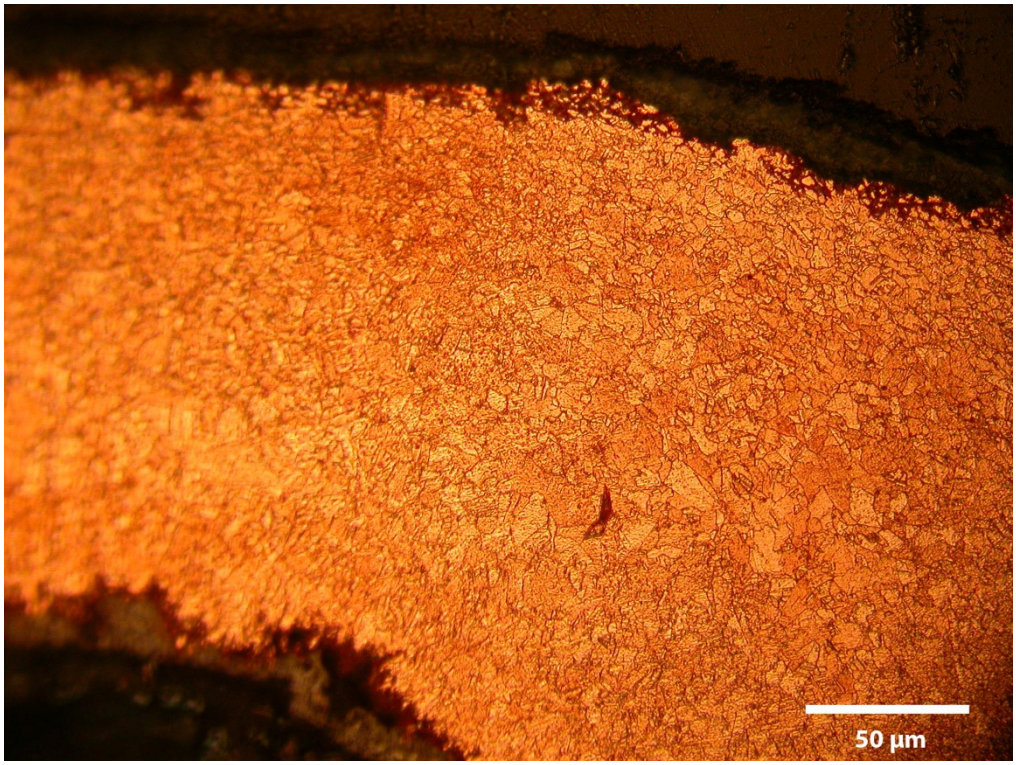

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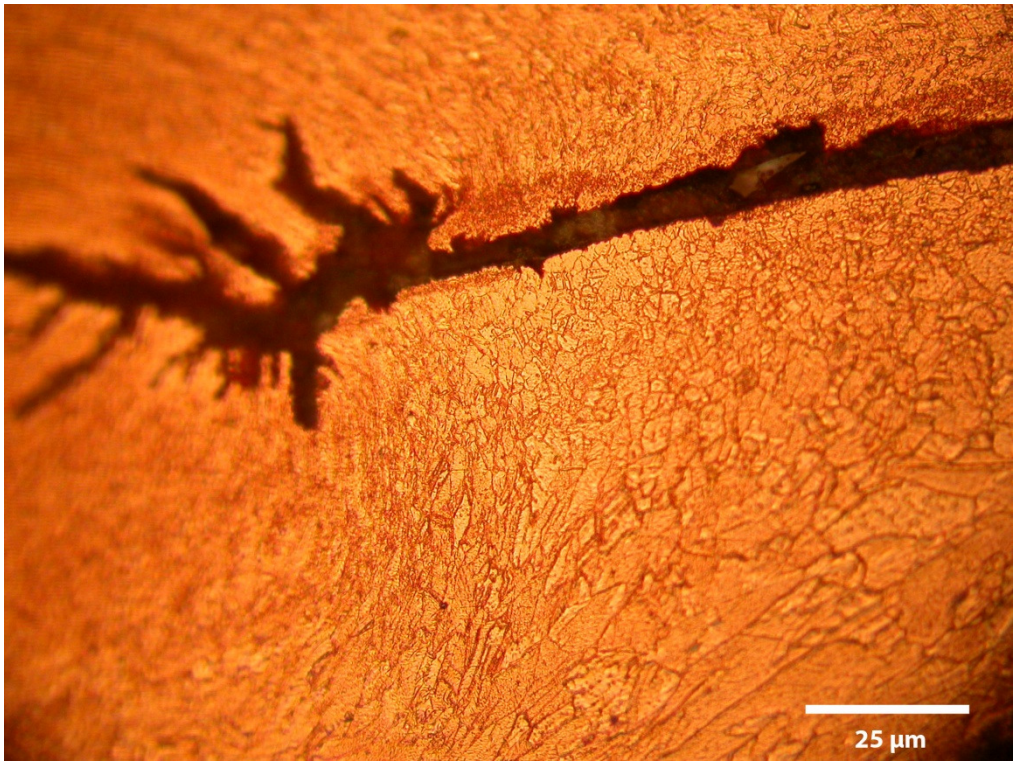

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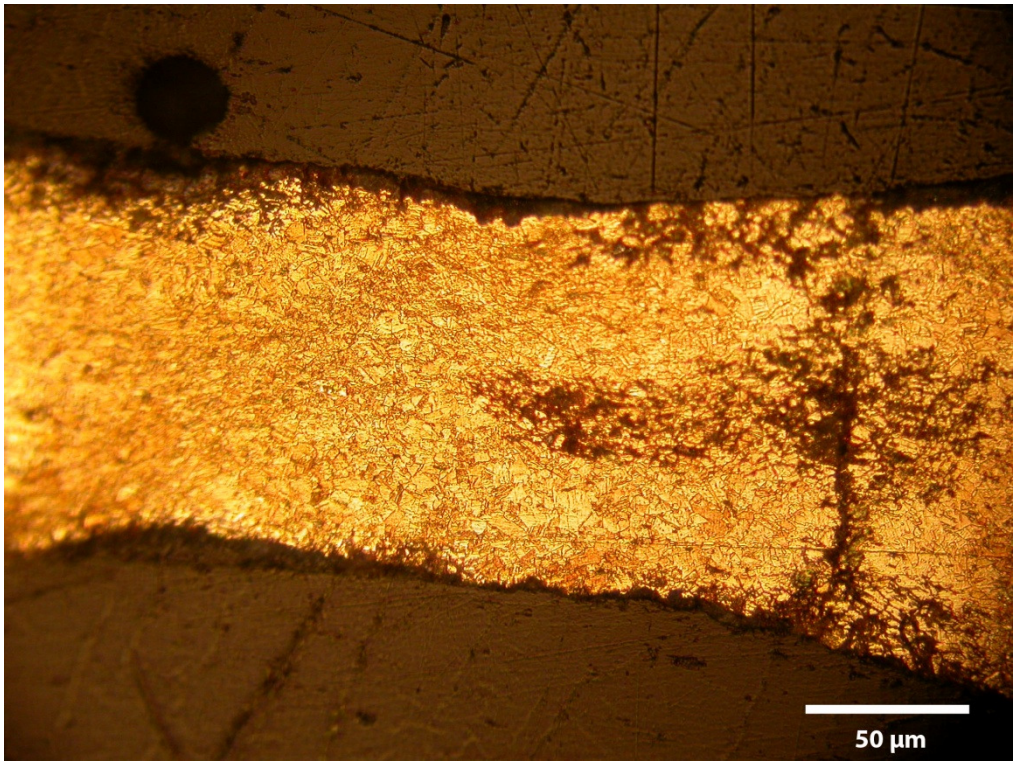

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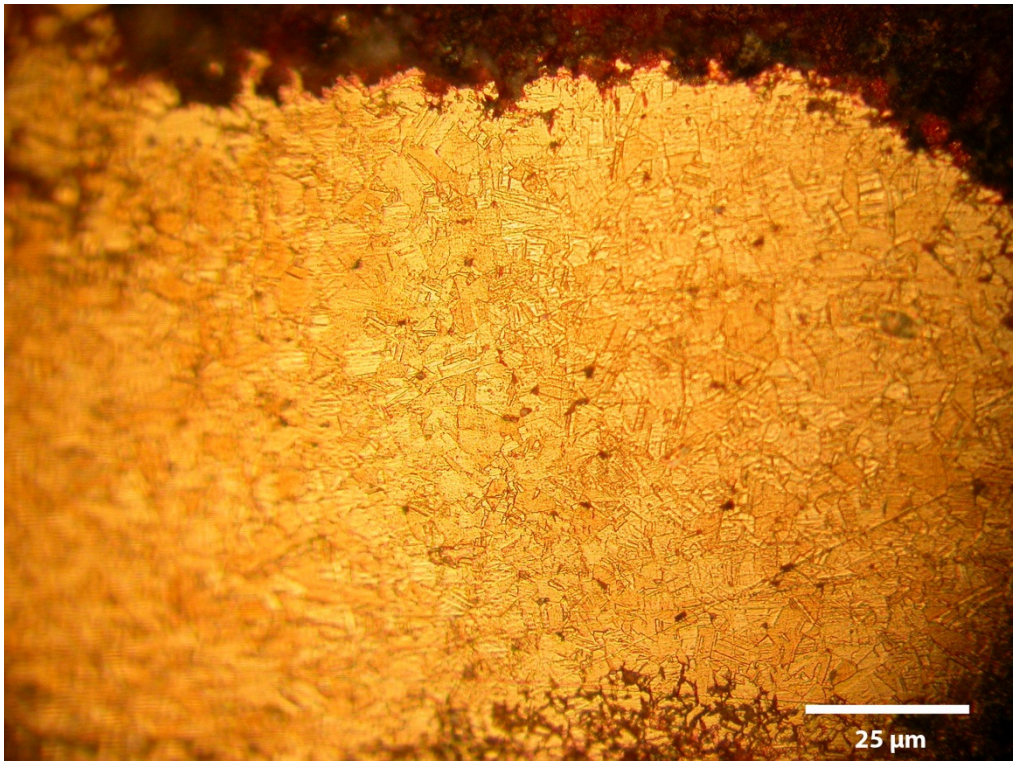

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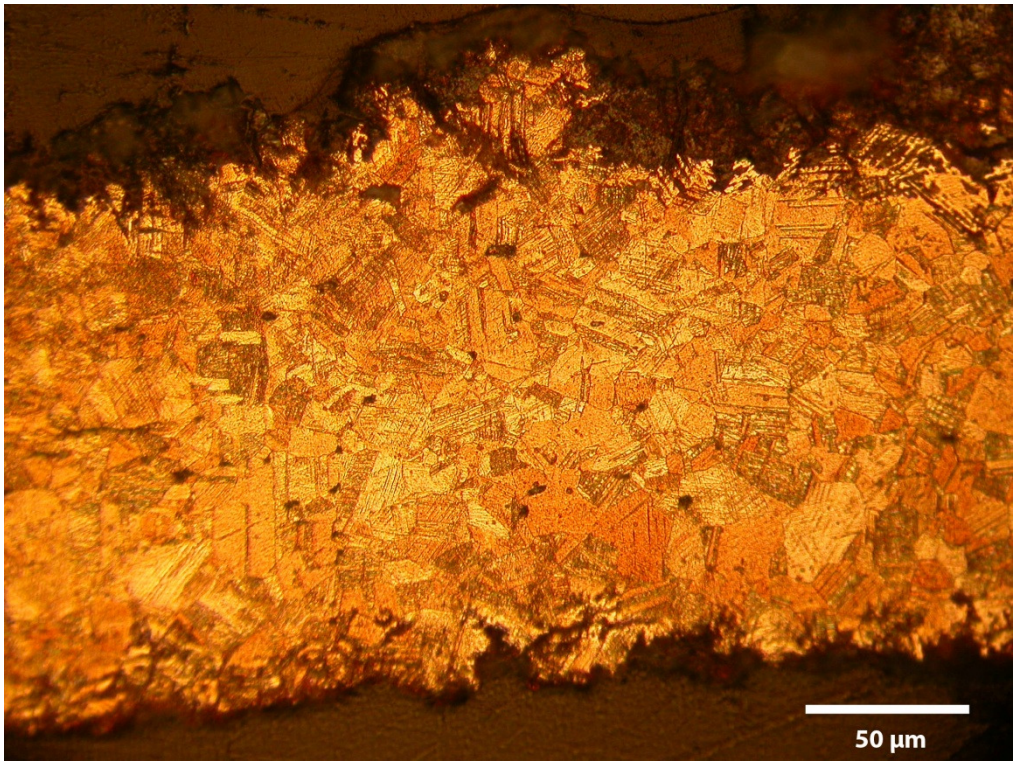

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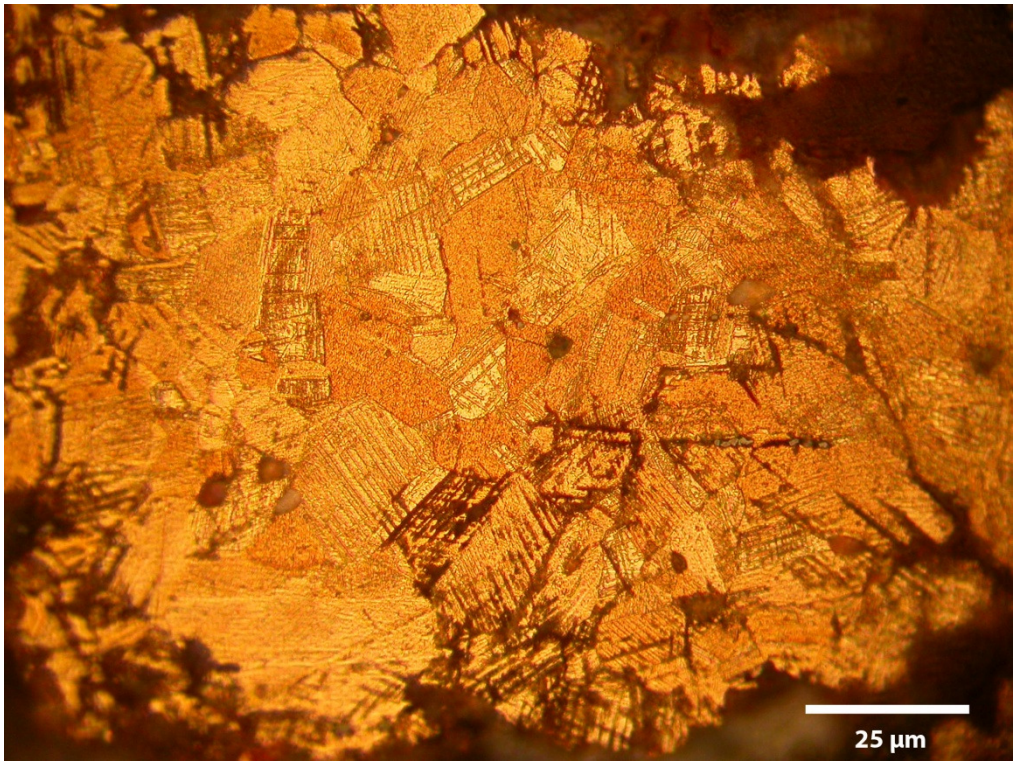

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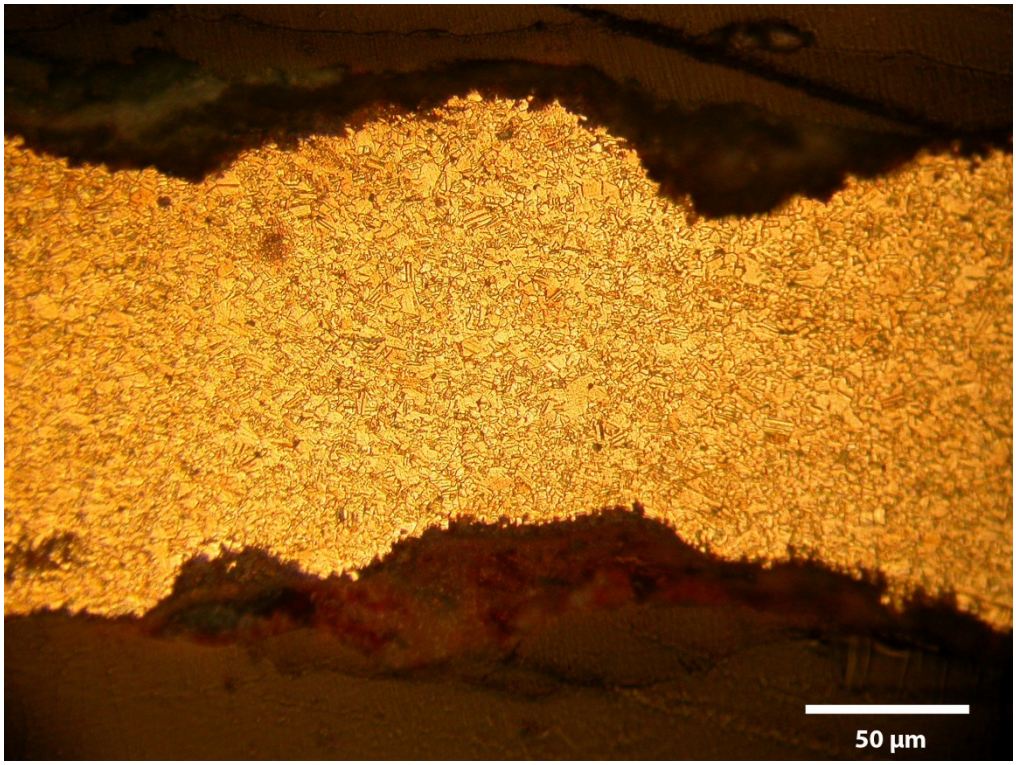

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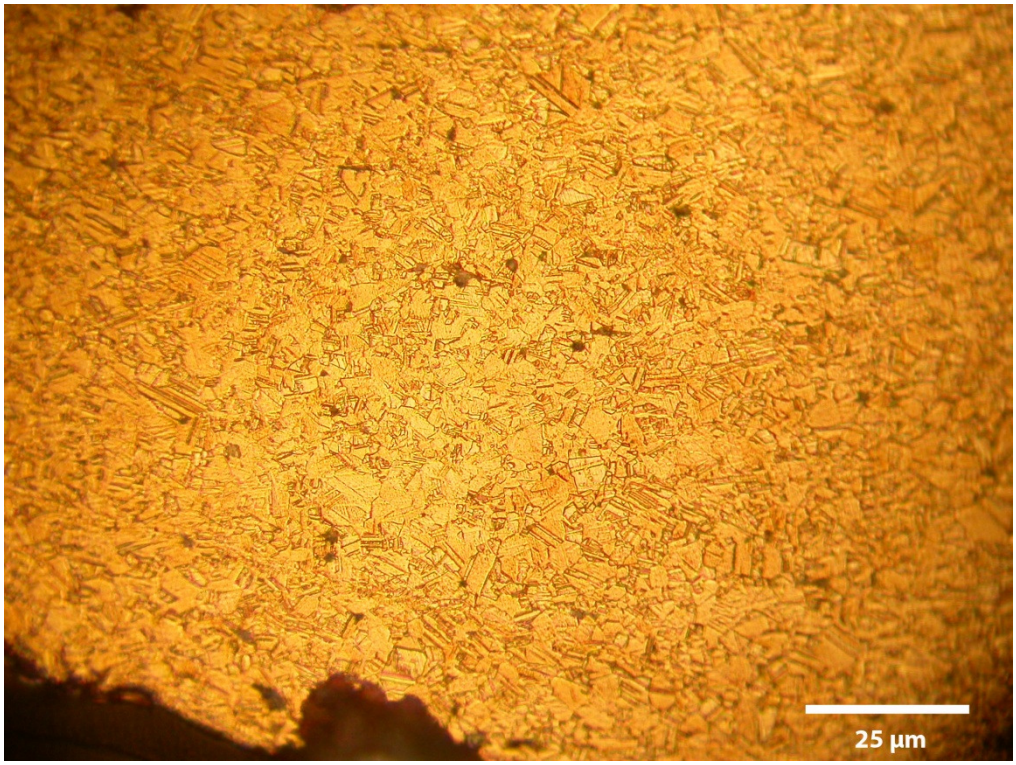

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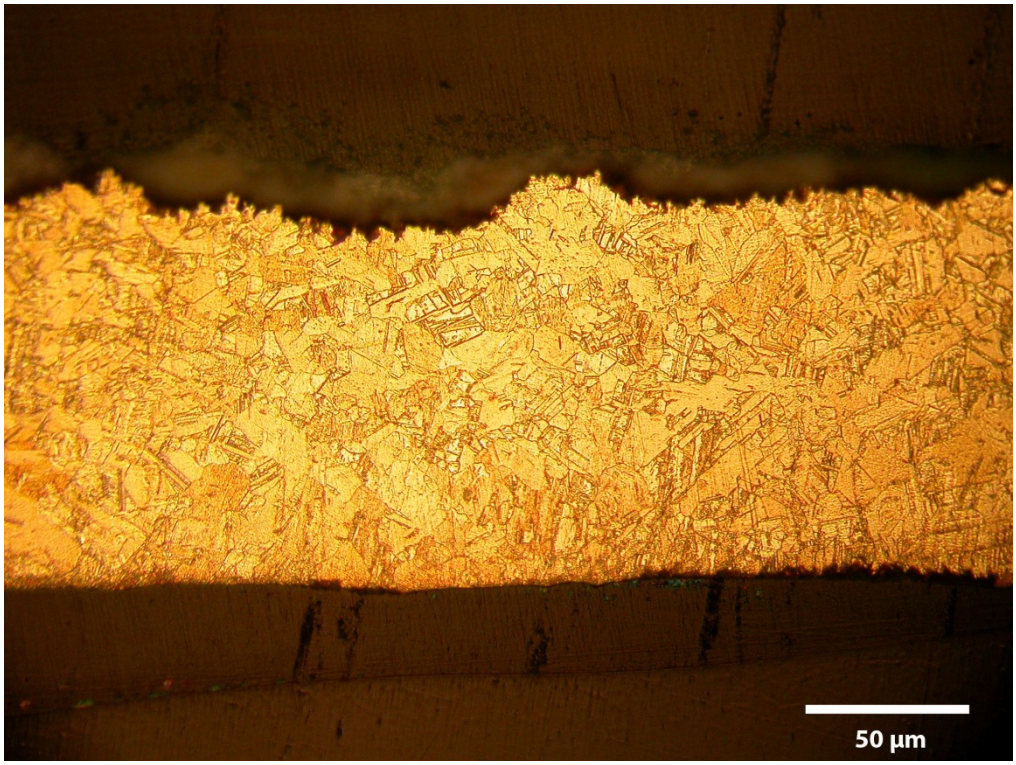

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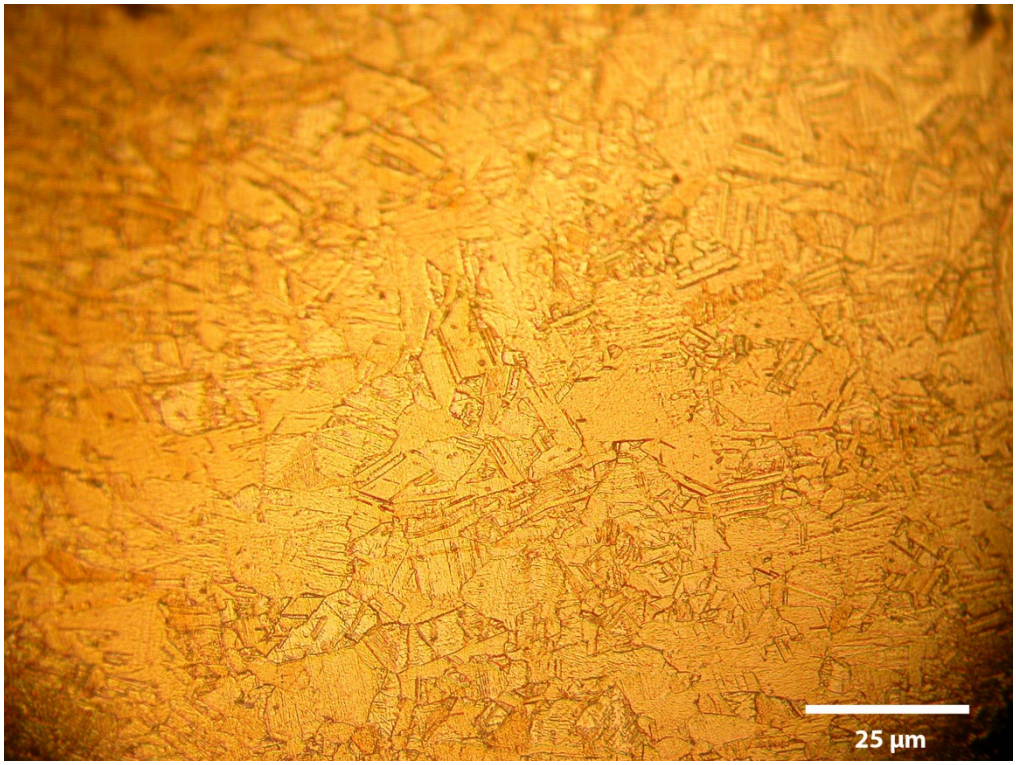

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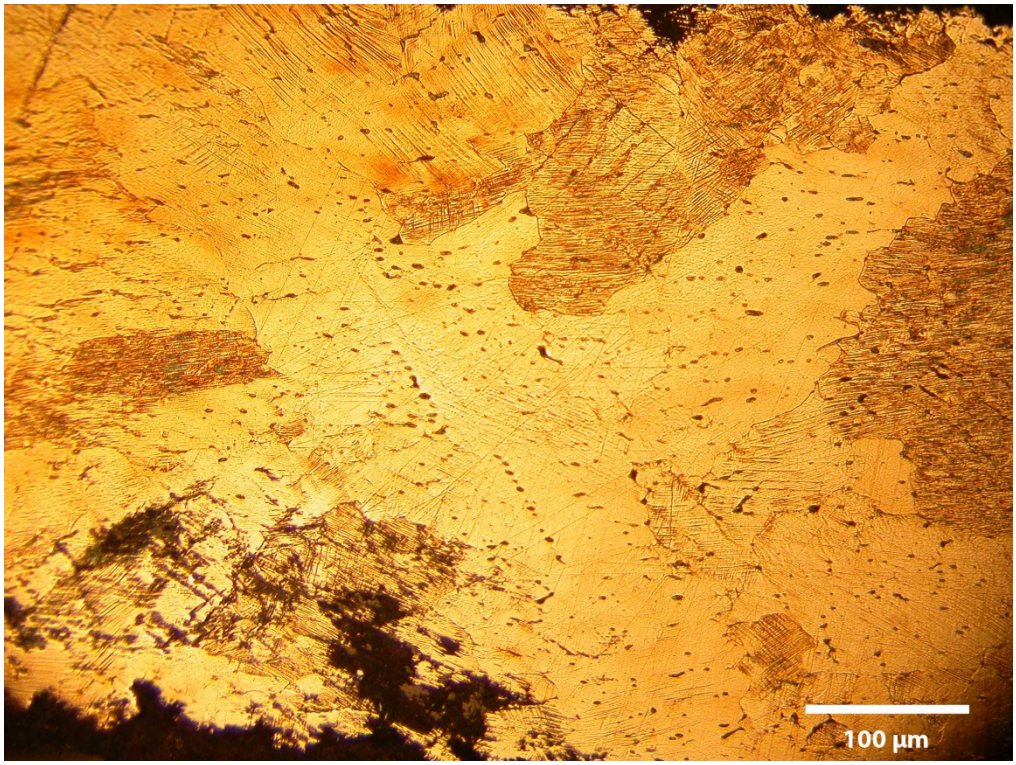

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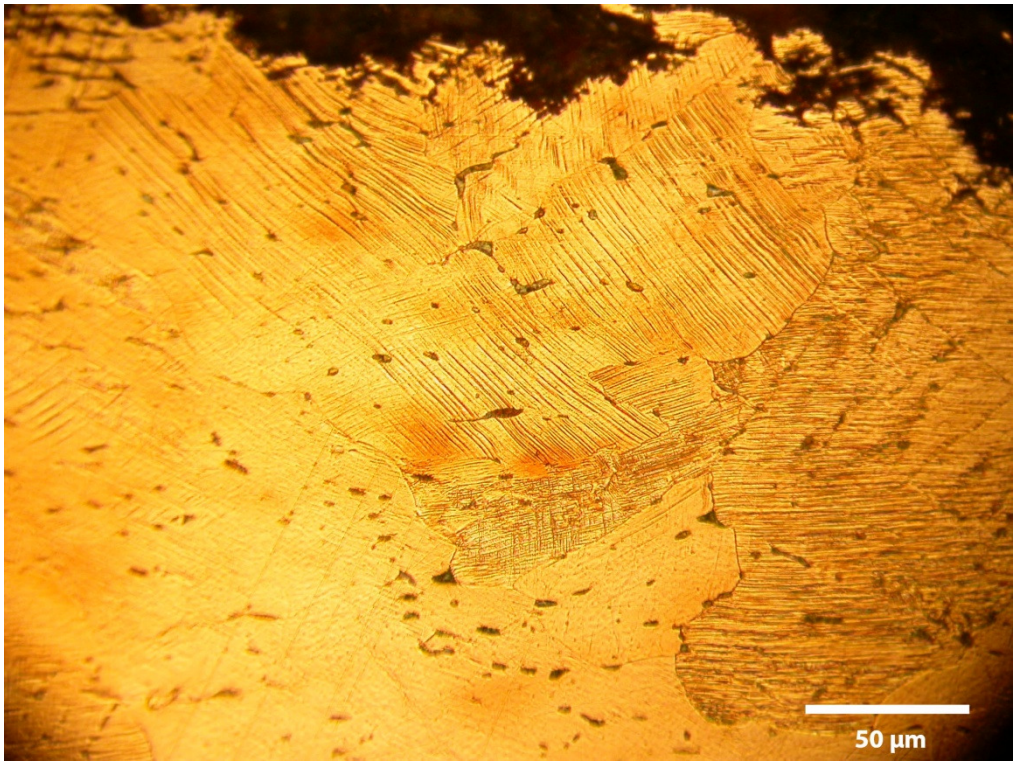

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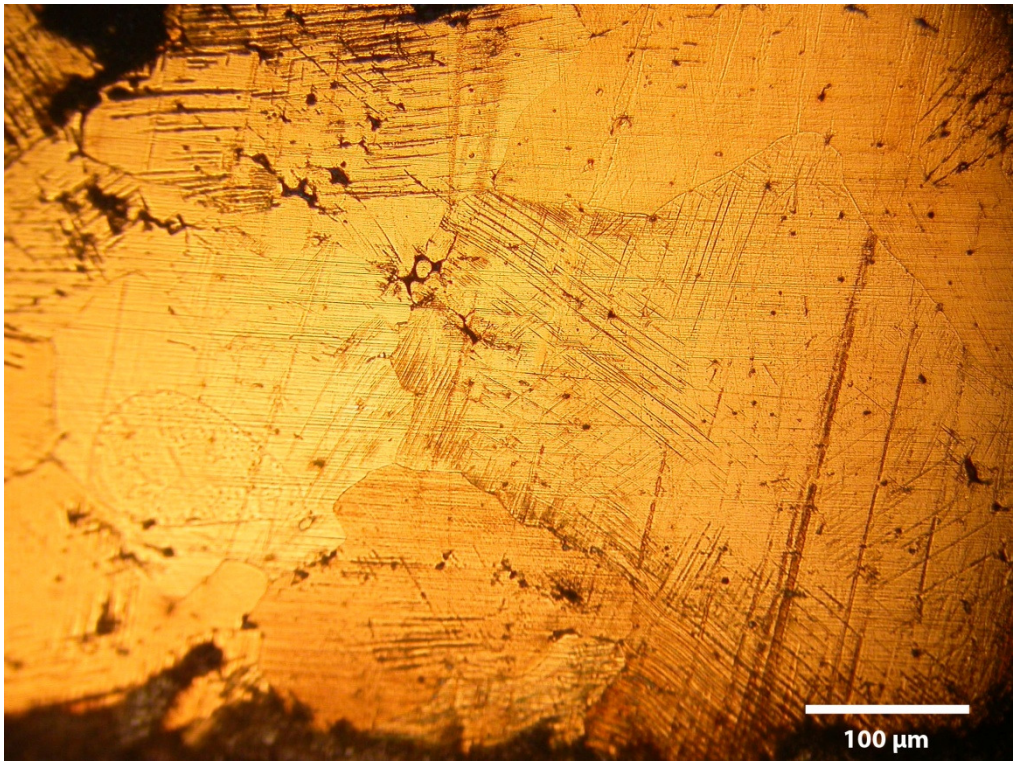

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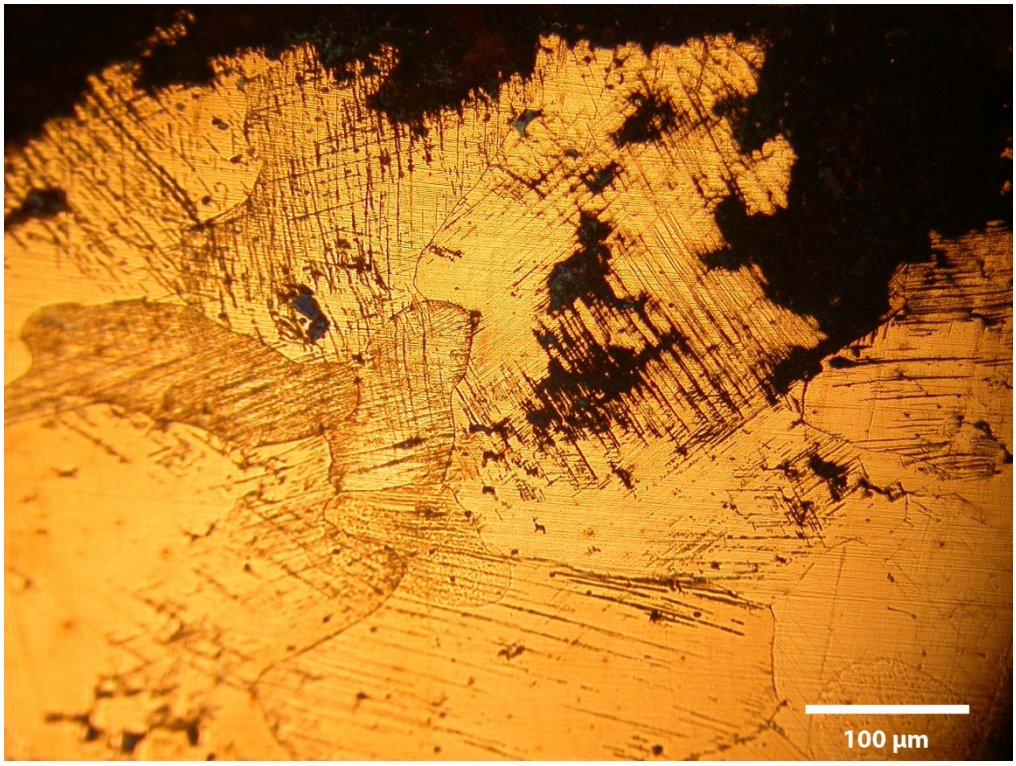

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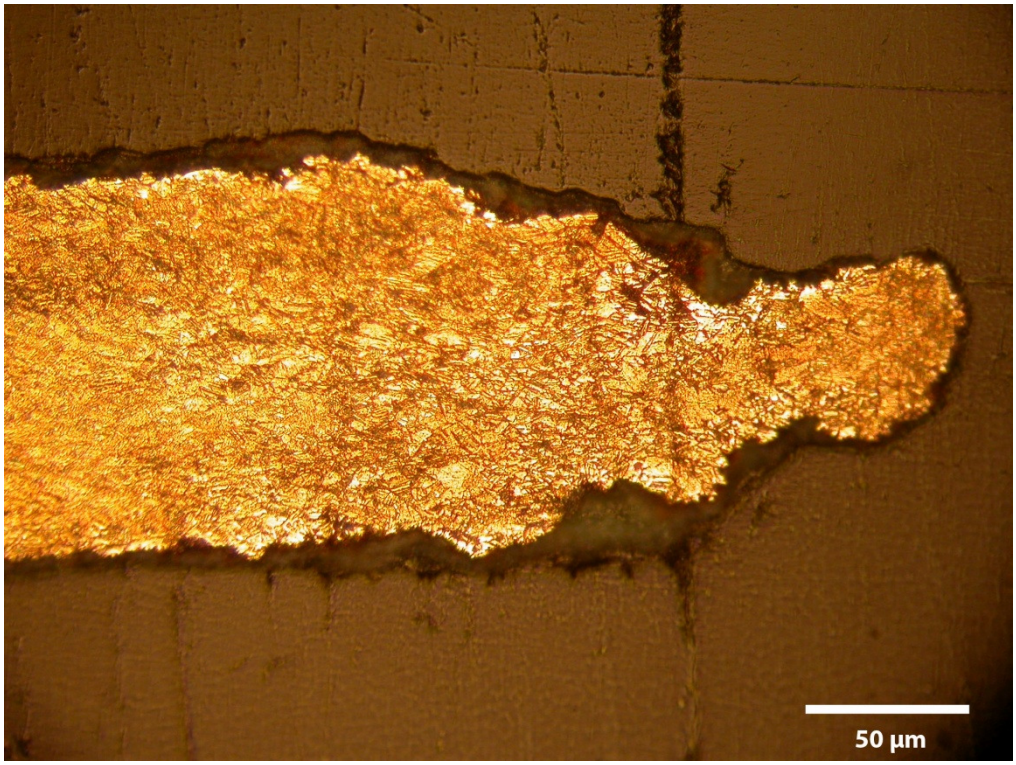

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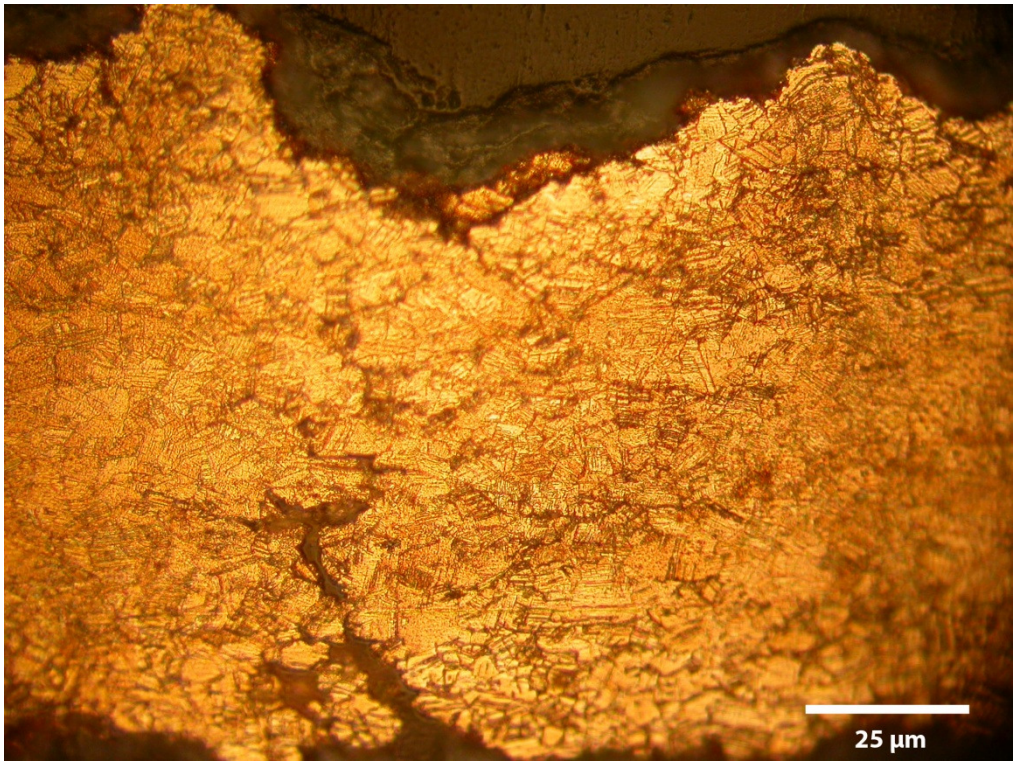

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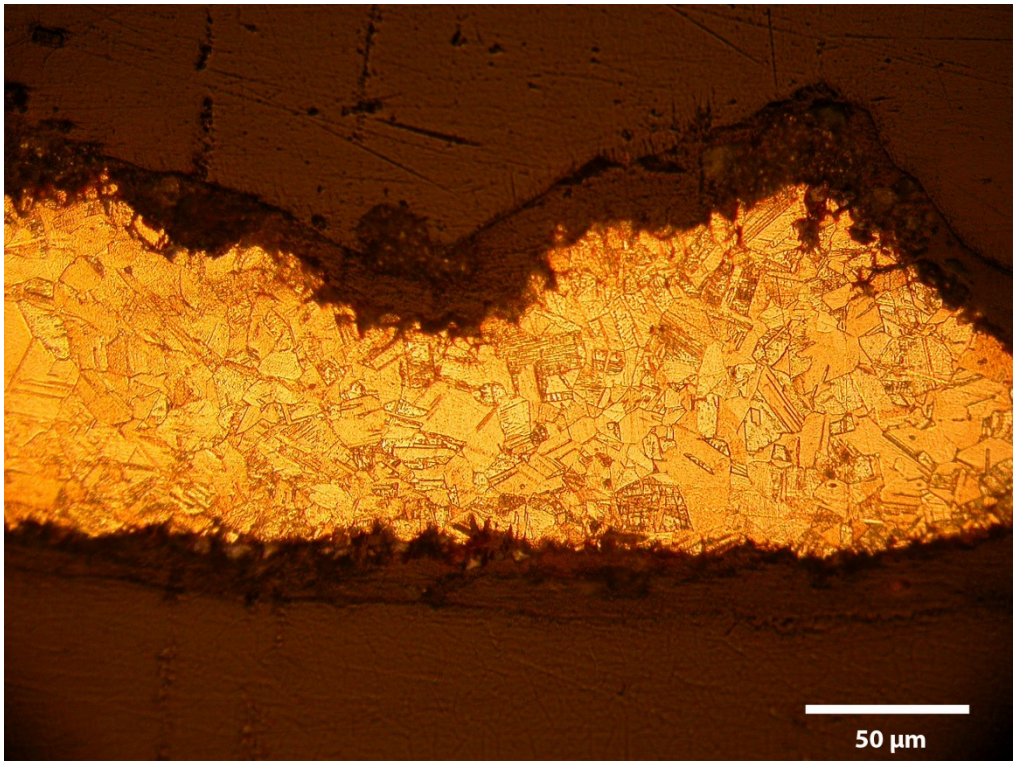

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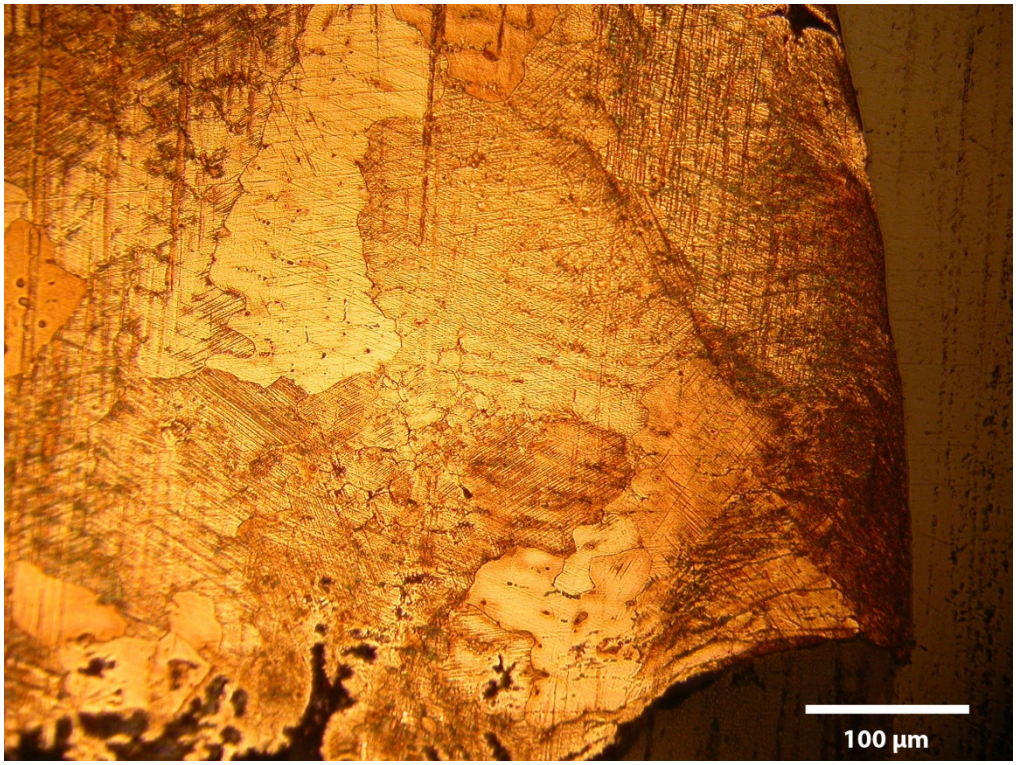
Figure A3.122 GLC2602



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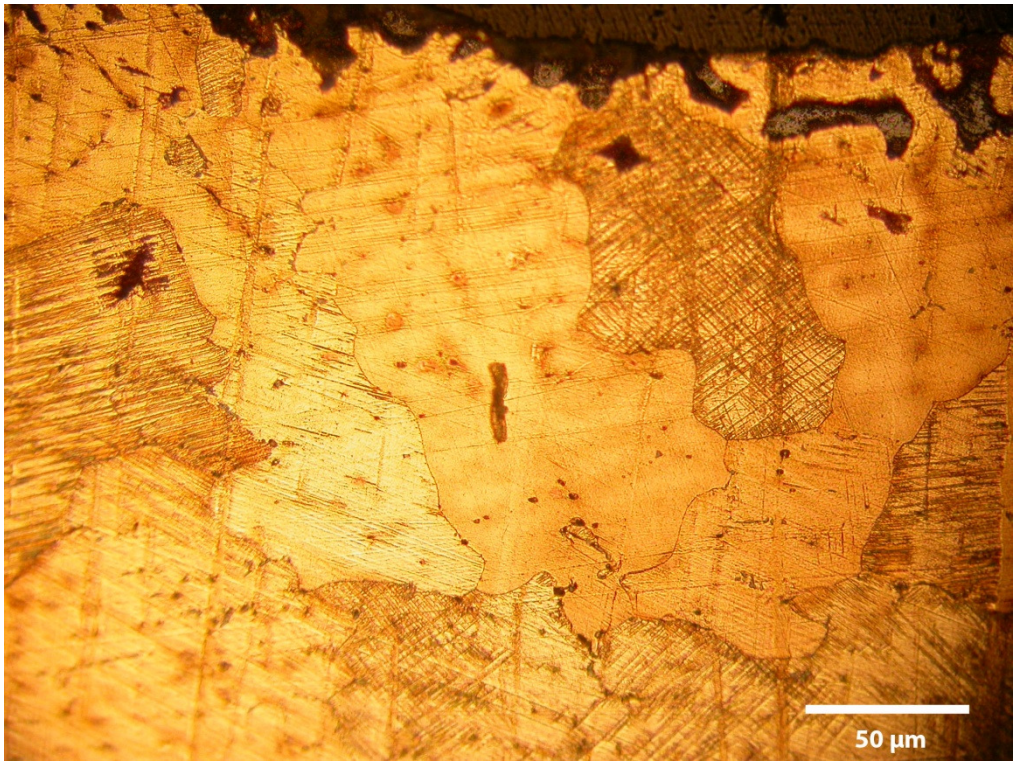

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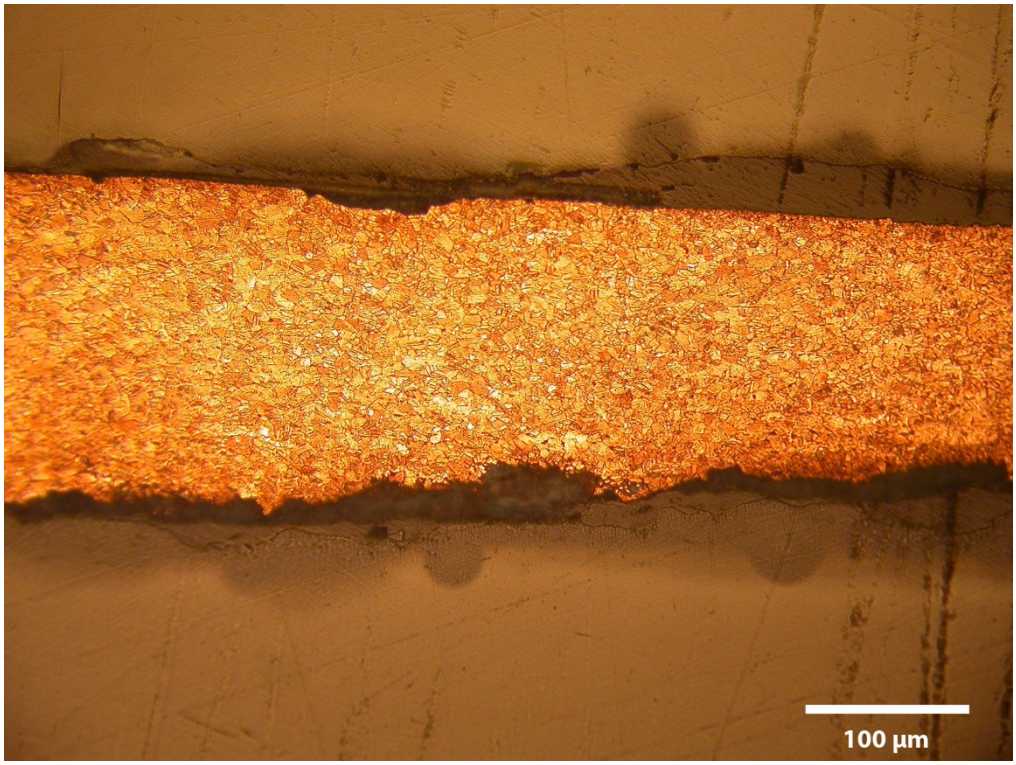

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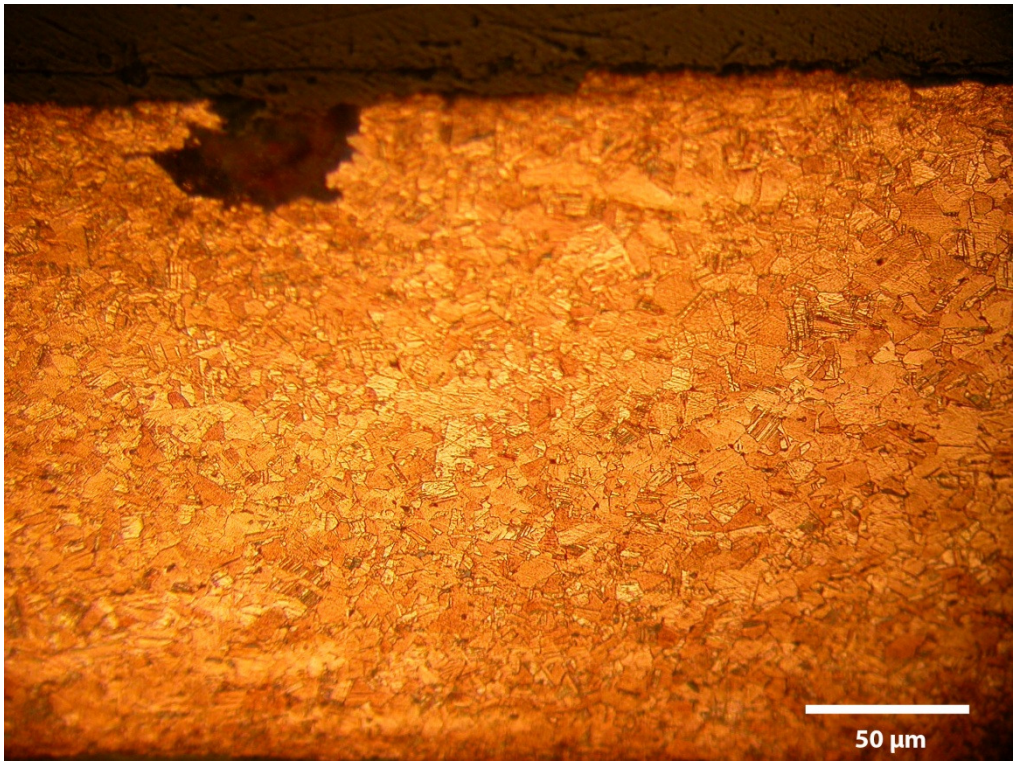


Figure A3.126 GLC2741

Figure A3.127 GLC2741

A3.7 Kalkriese

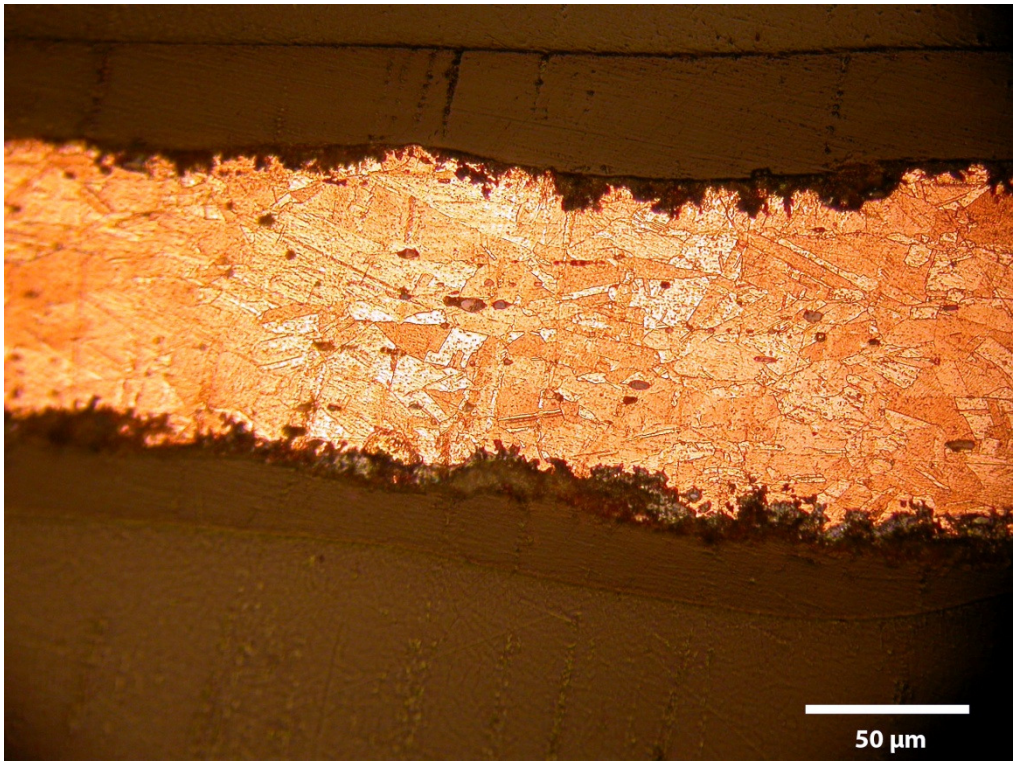
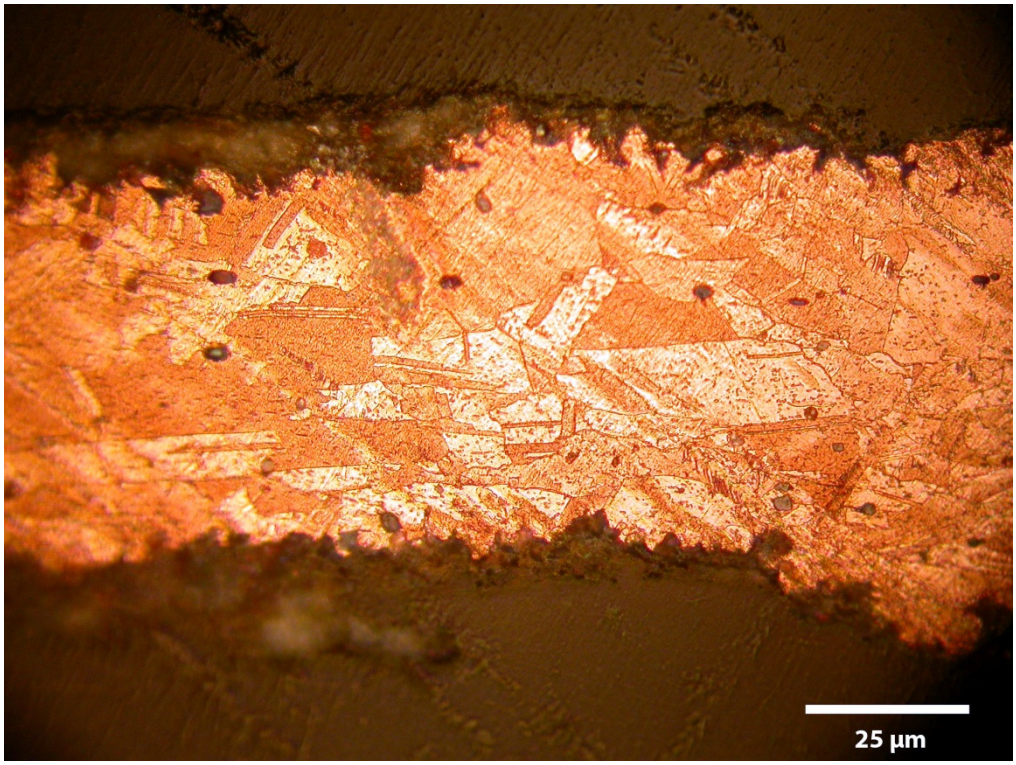


Figure A3.128 K186



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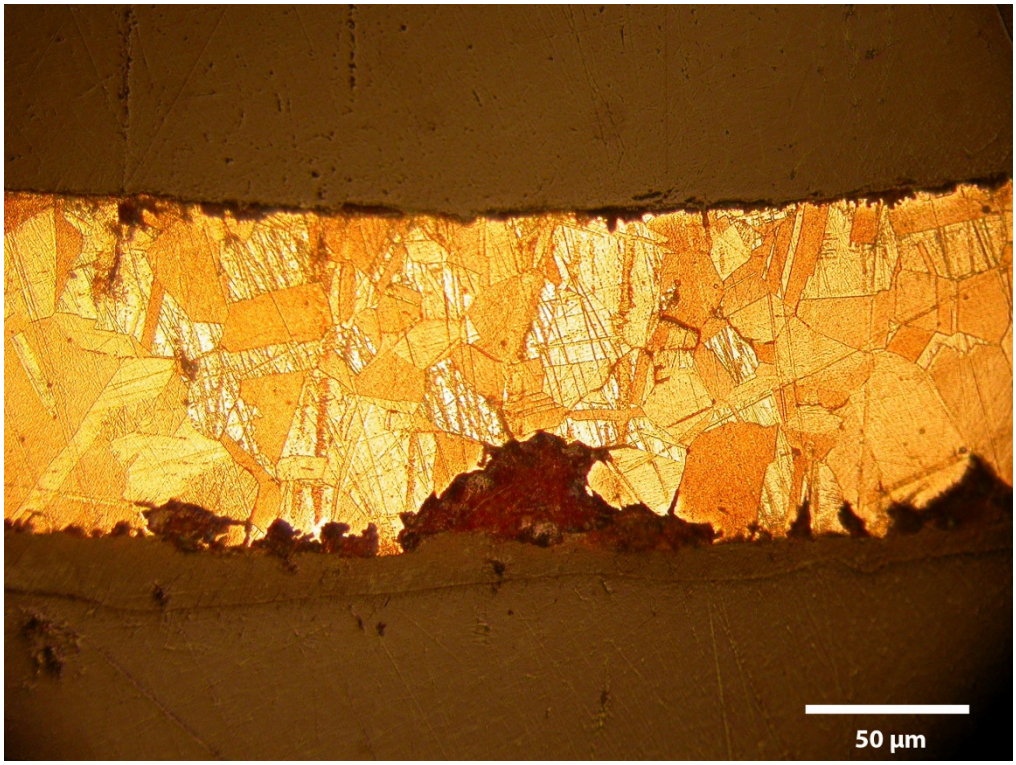

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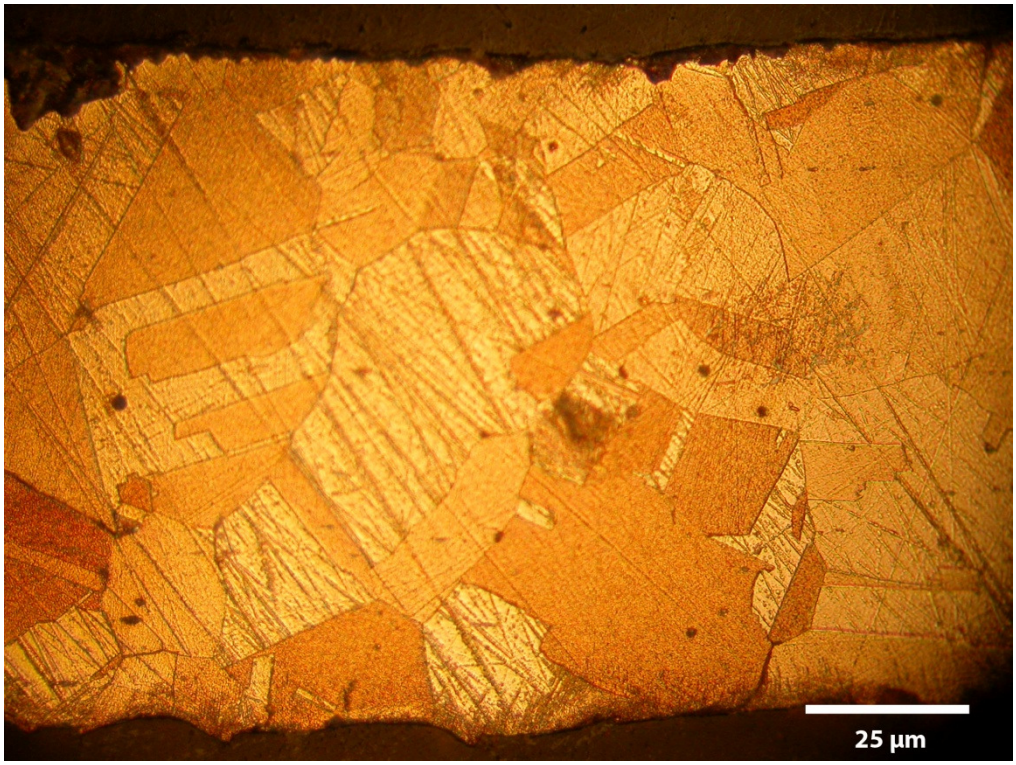

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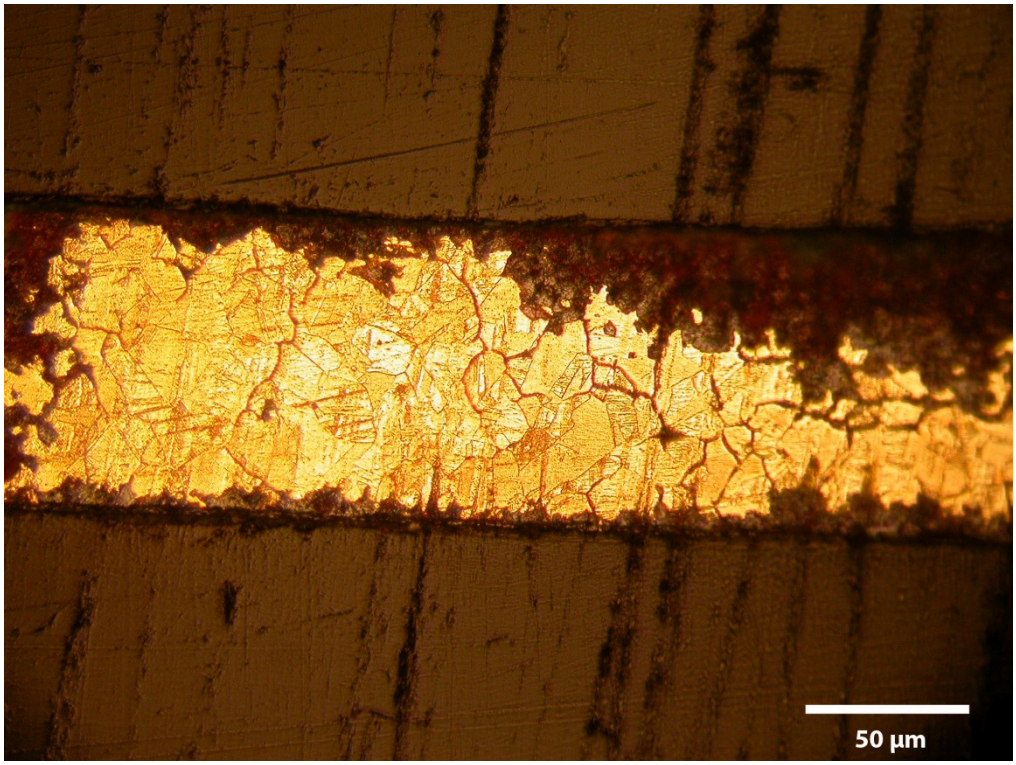

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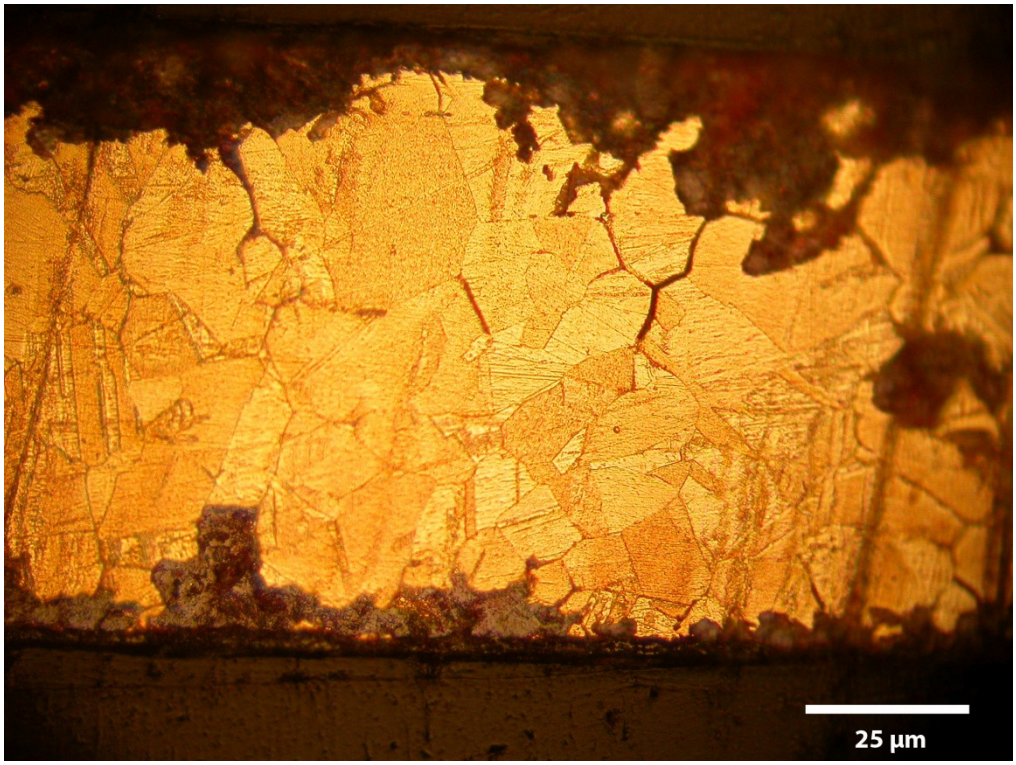


Figure A3.133 K2002

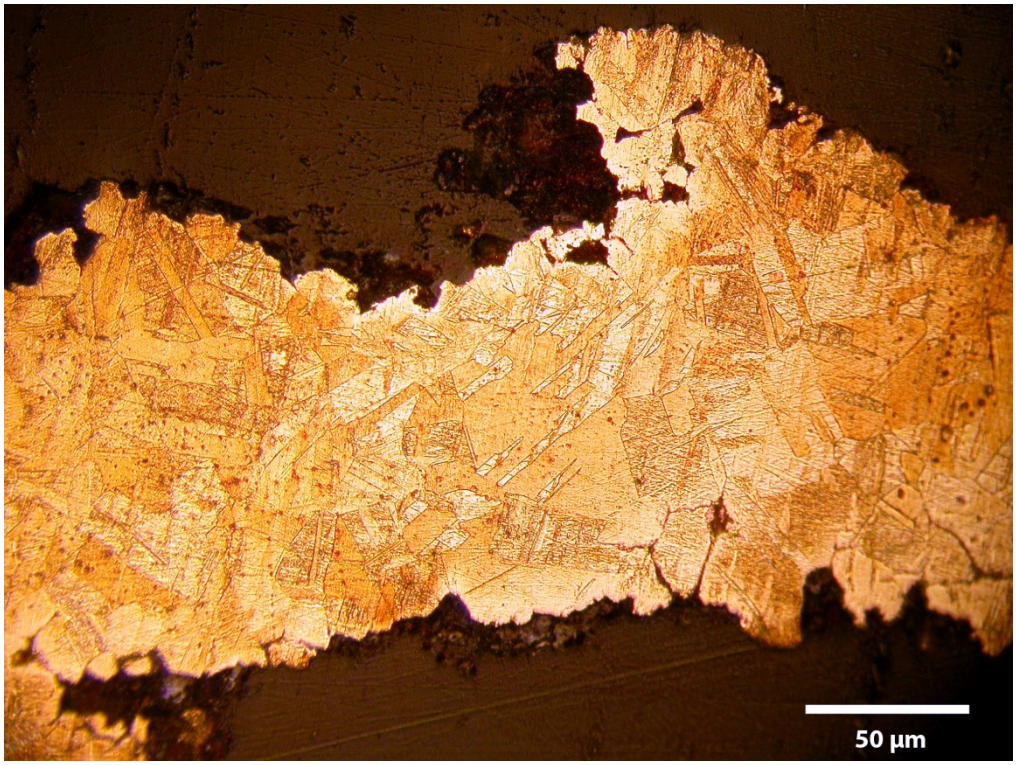
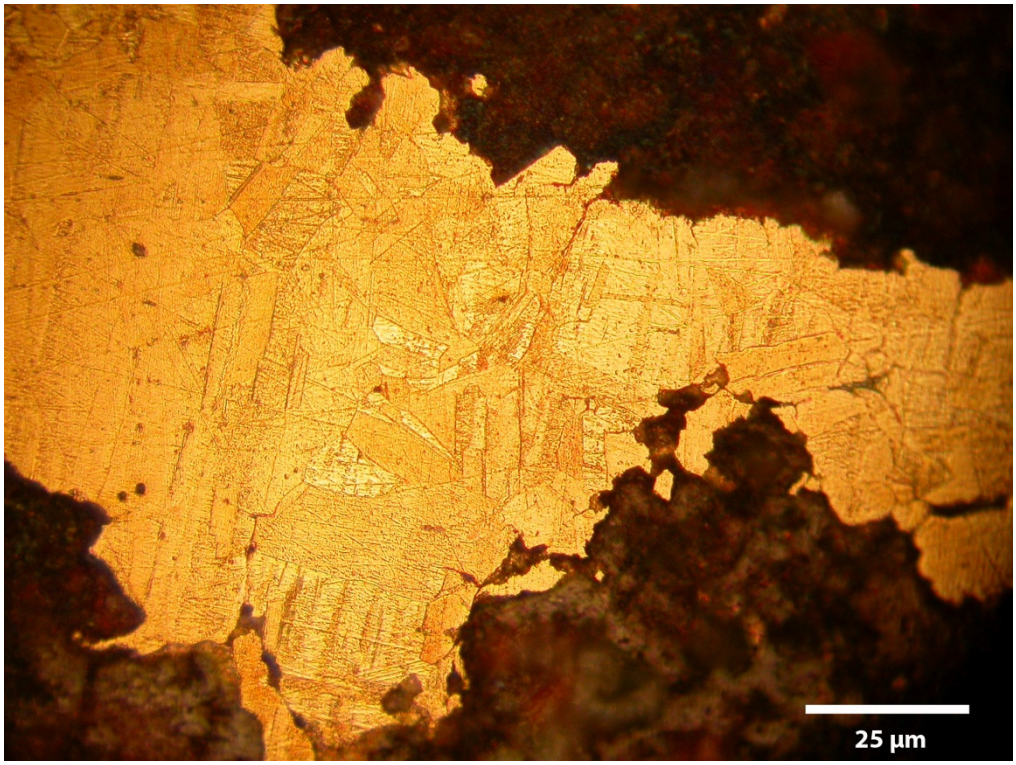


Figure A3.134 K2030



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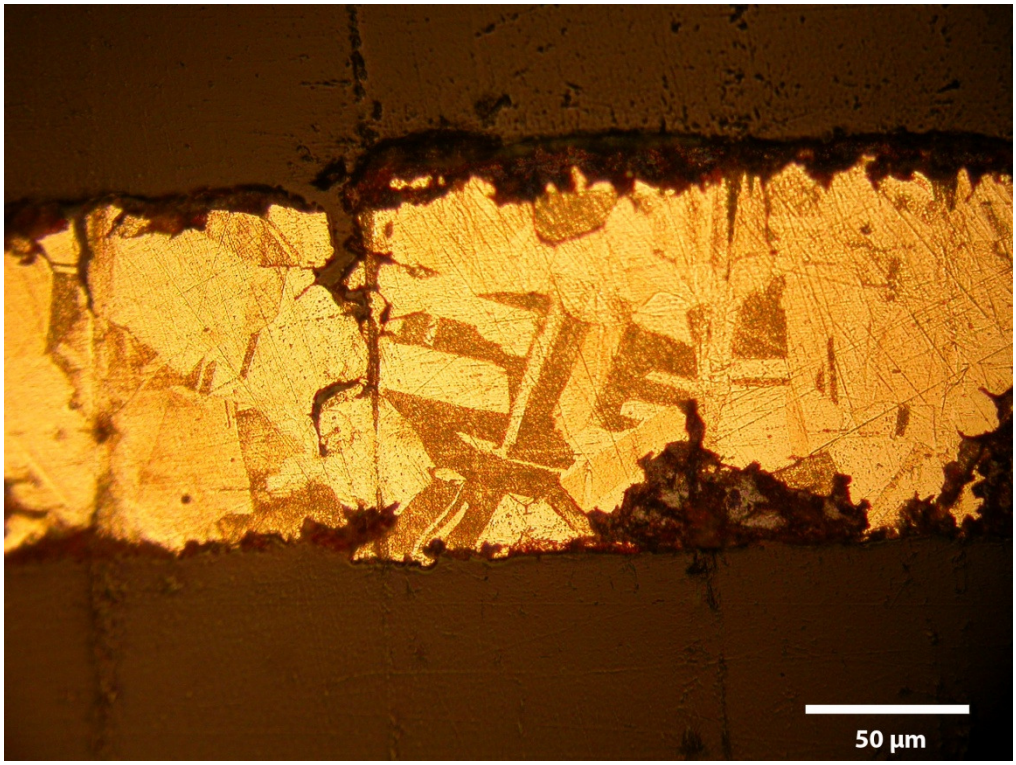

Figure A3.136 K3223

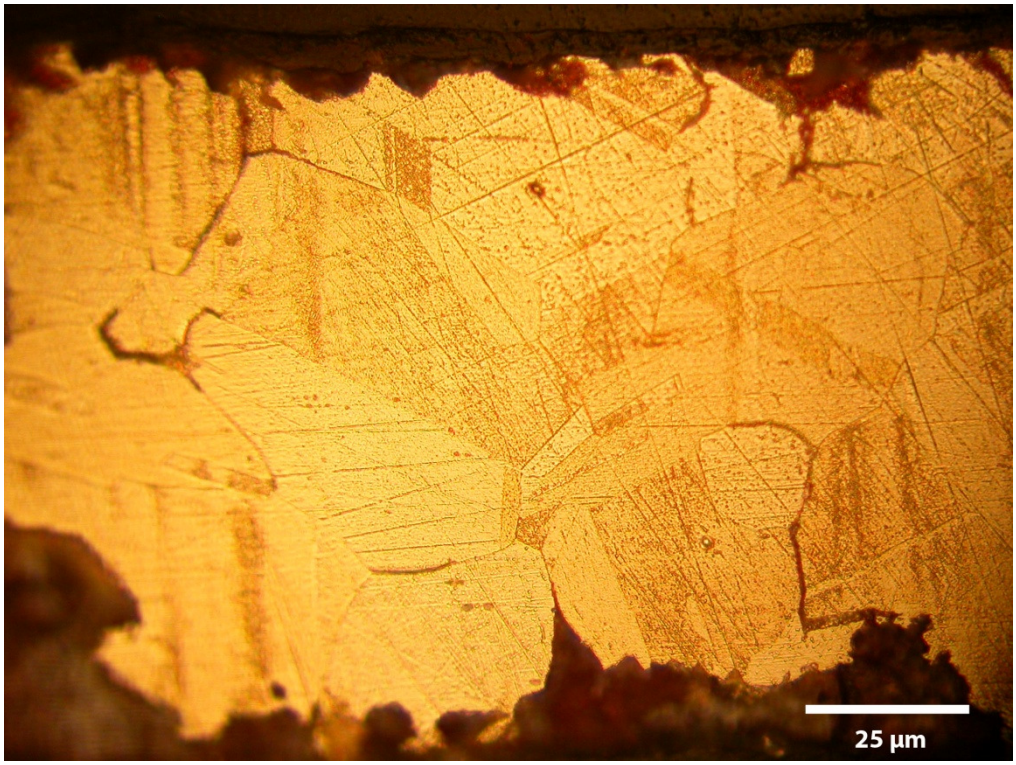

Figure A3.137 K3223

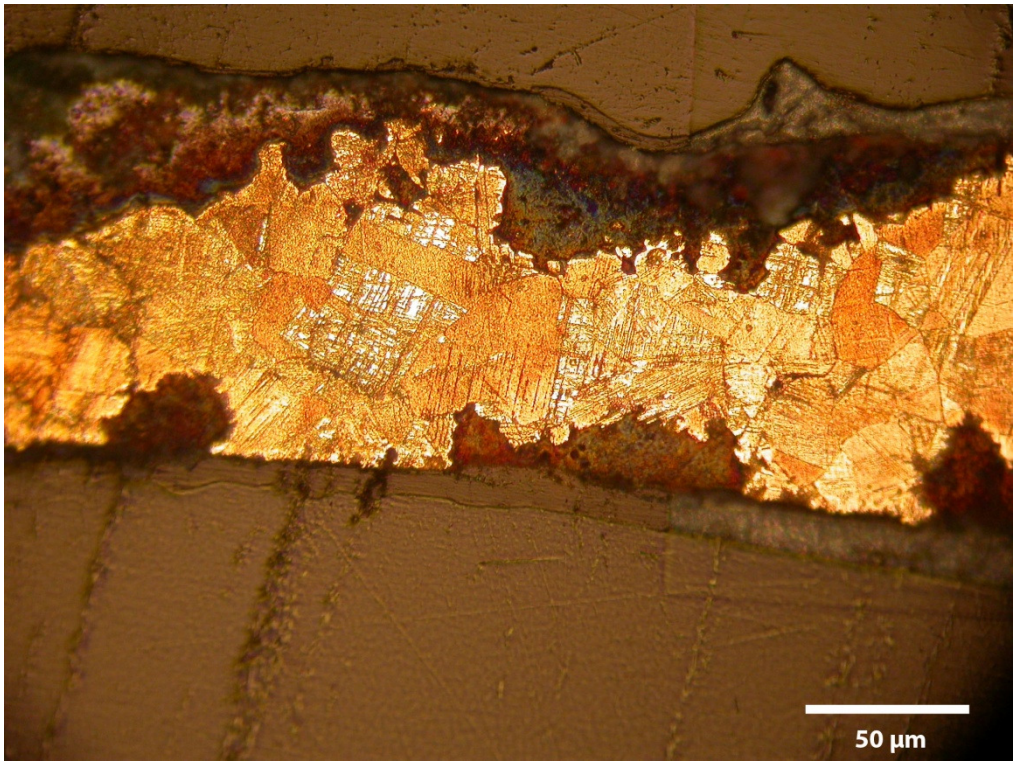

Figure A3.138 K3797

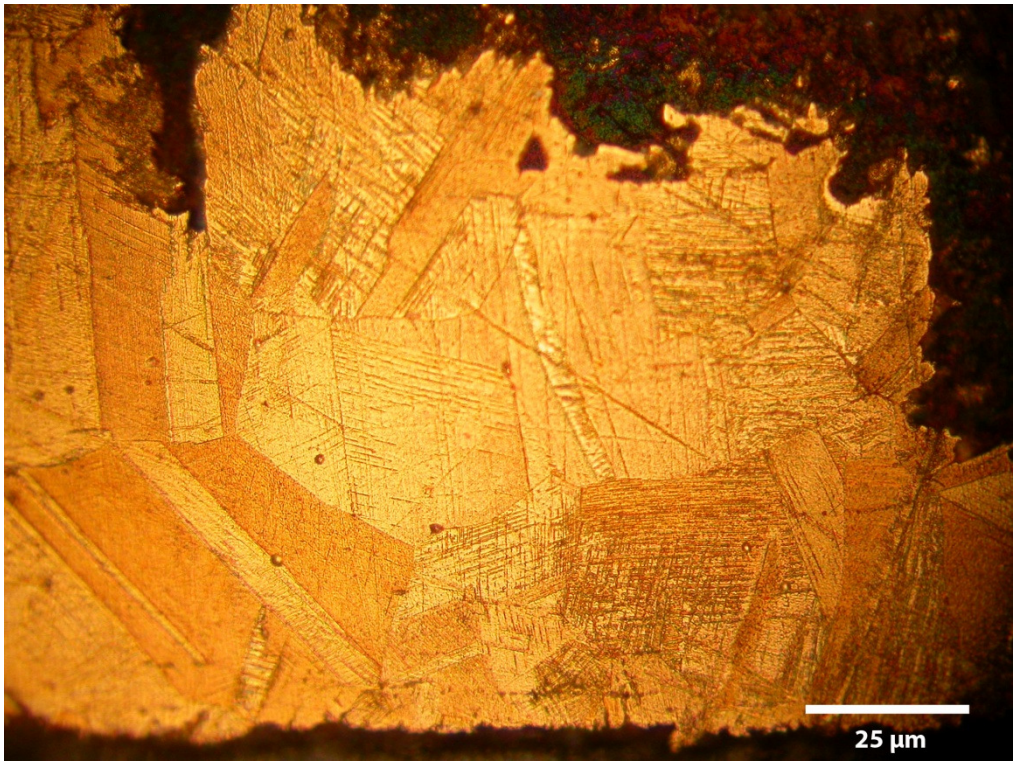

Figure A3.139 K3797

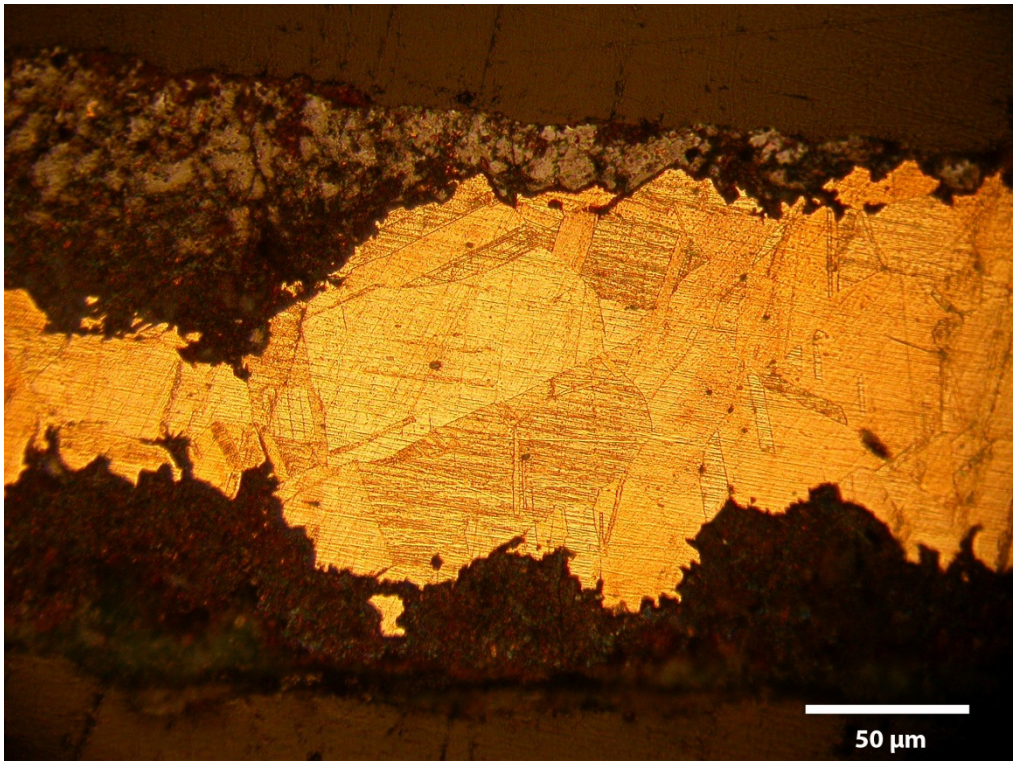

Figure A3.140 K10282

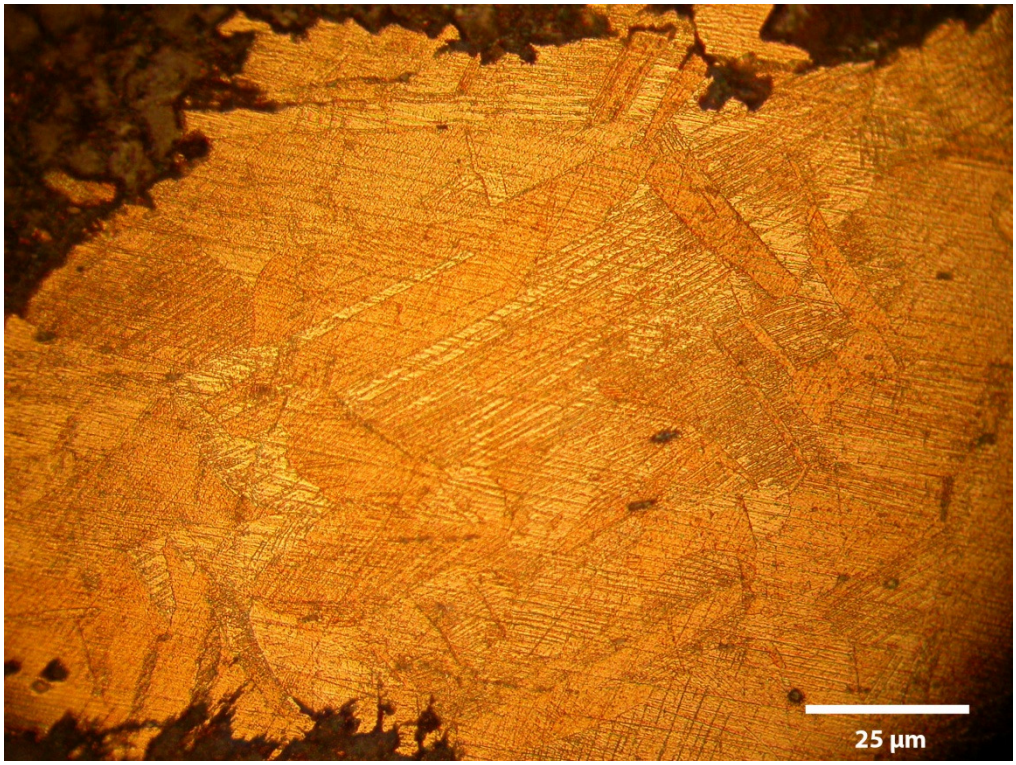

Figure A3.141 K10282

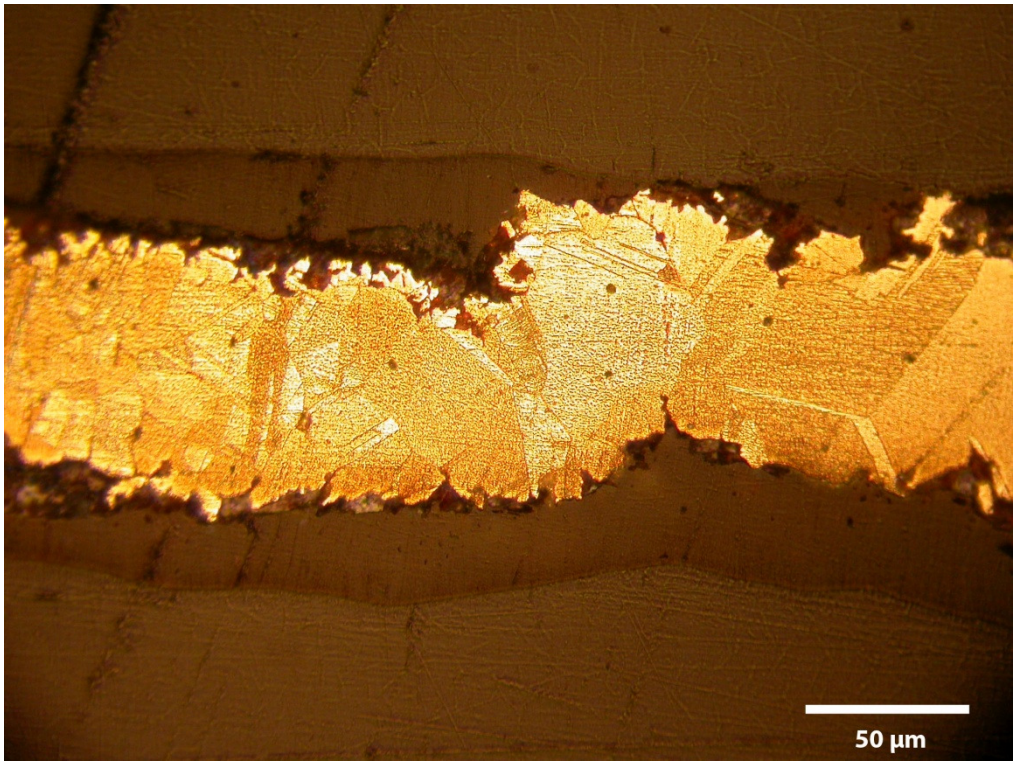

Figure A3.142 K10412

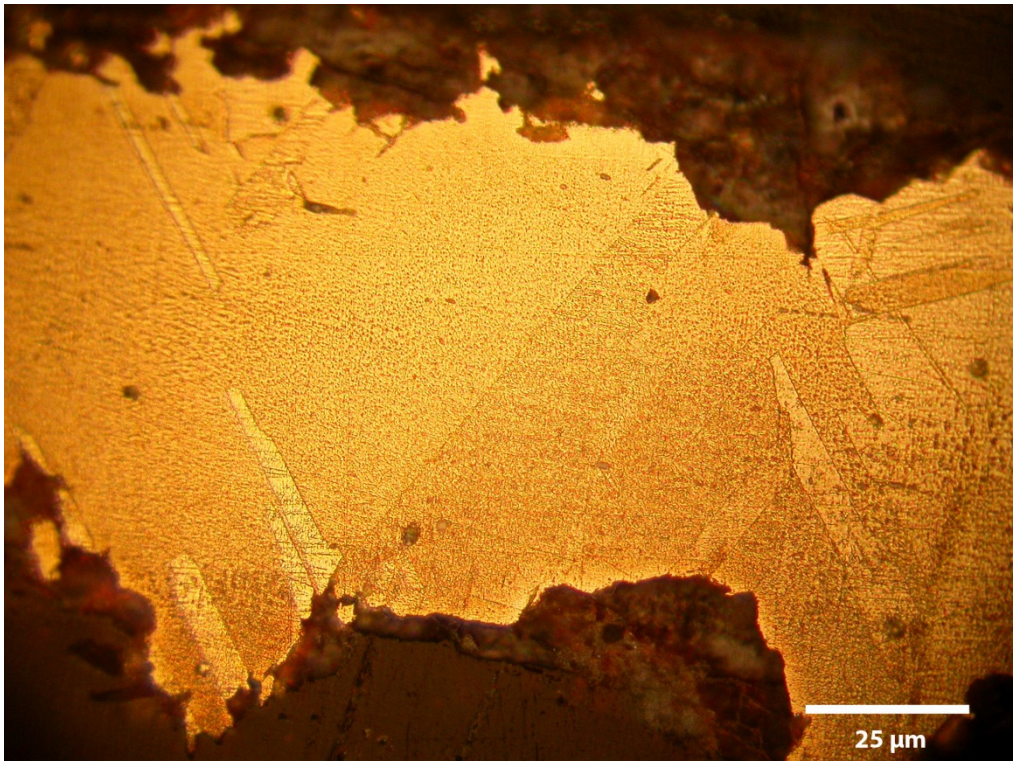

Figure A3.143 K10412

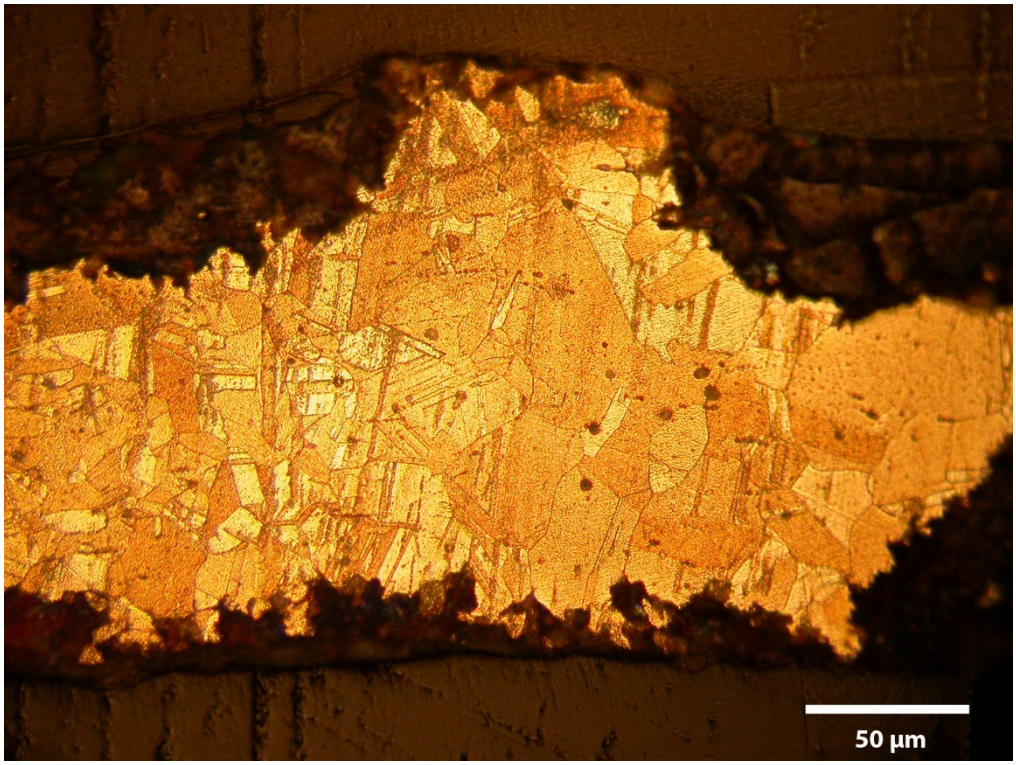

Figure A3.144 K10413

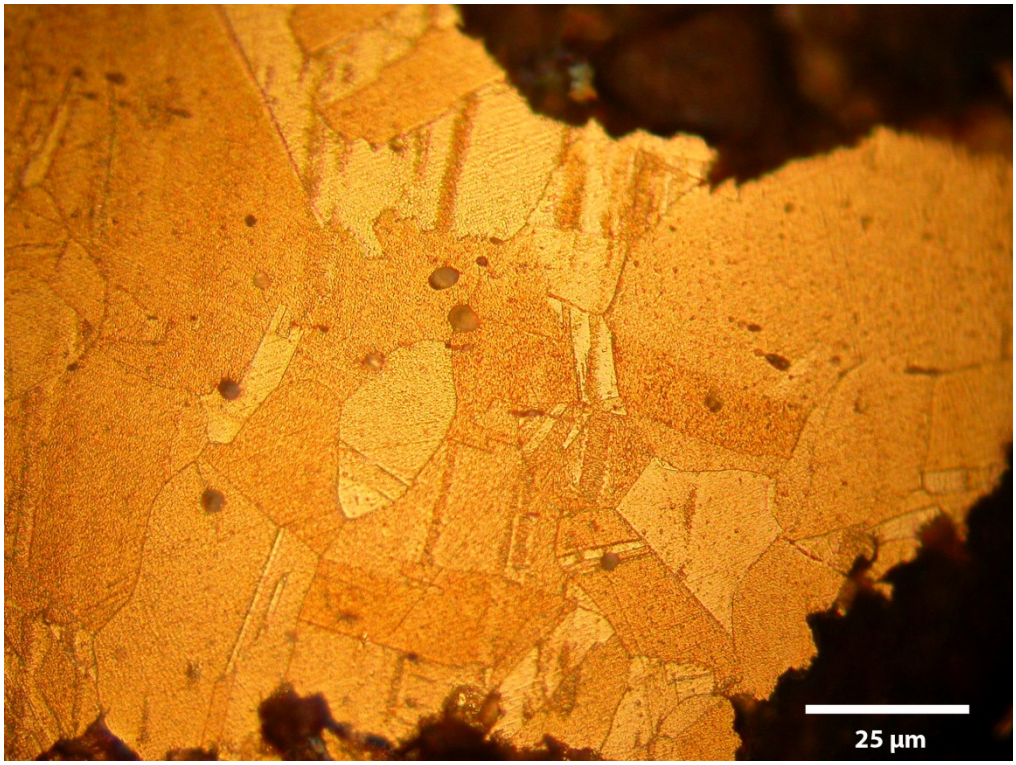

Figure A3.145 K10413

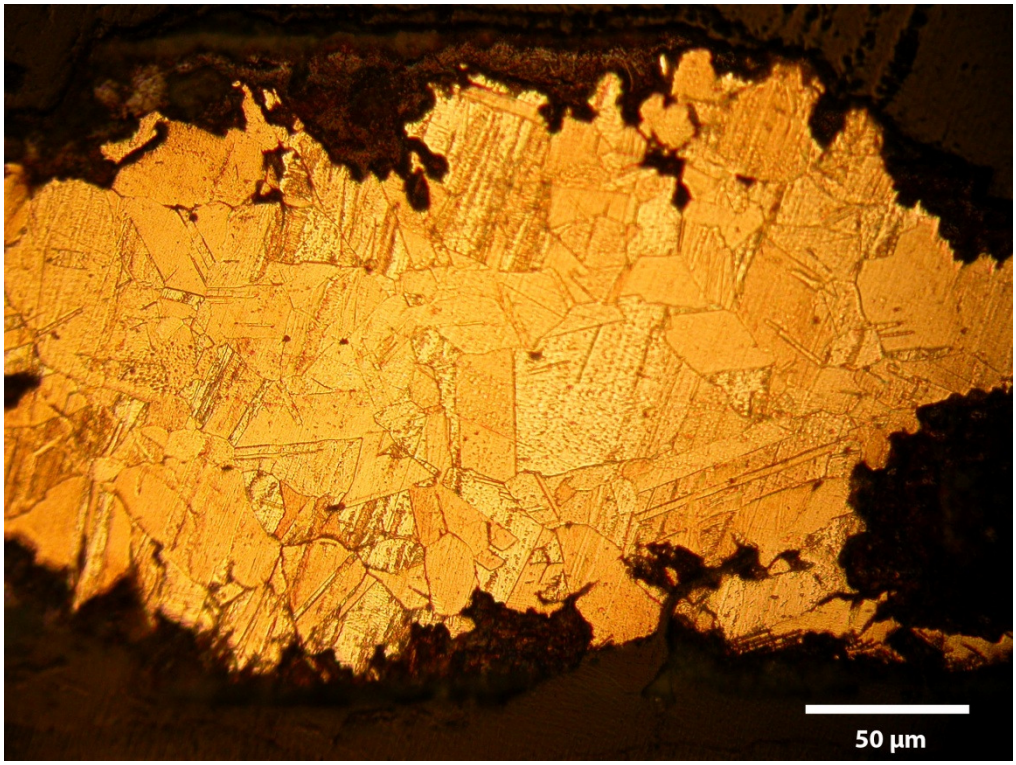

Figure A3.146 K10550

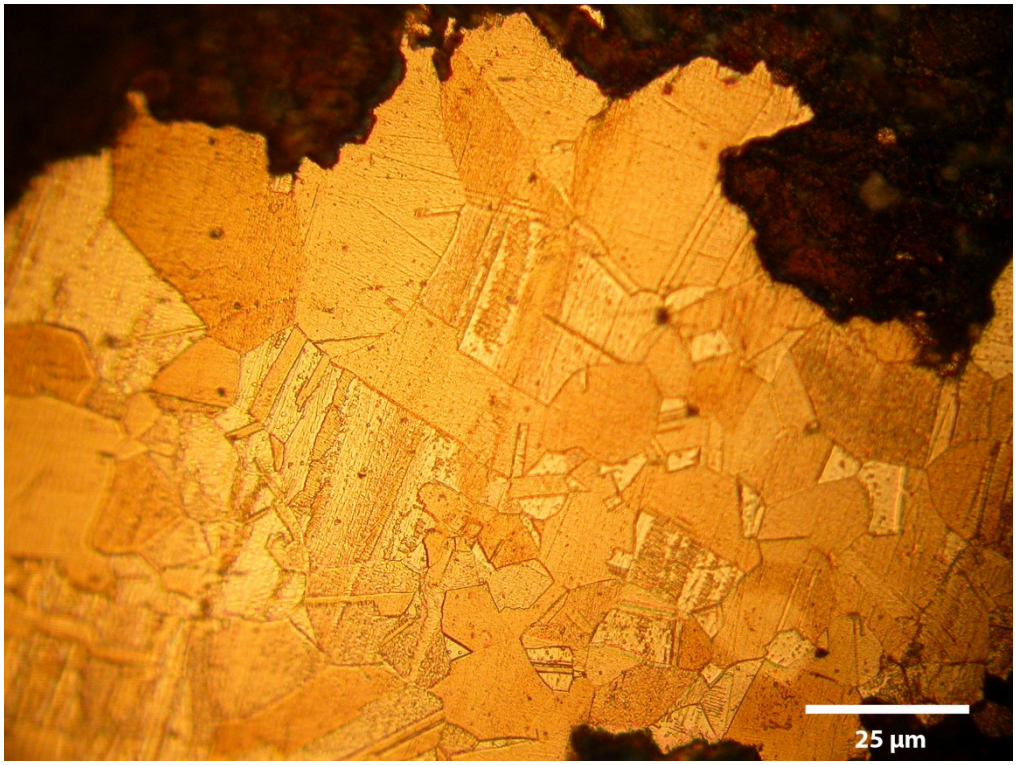

Figure A3.147 K10550

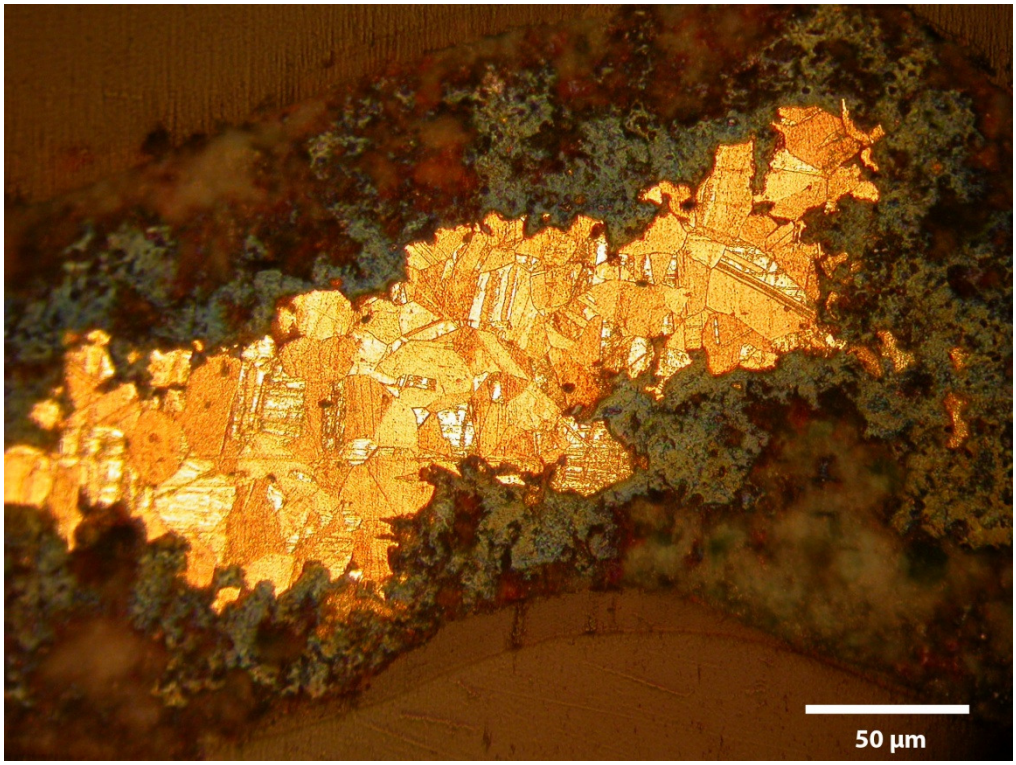

Figure A3.148 K10597

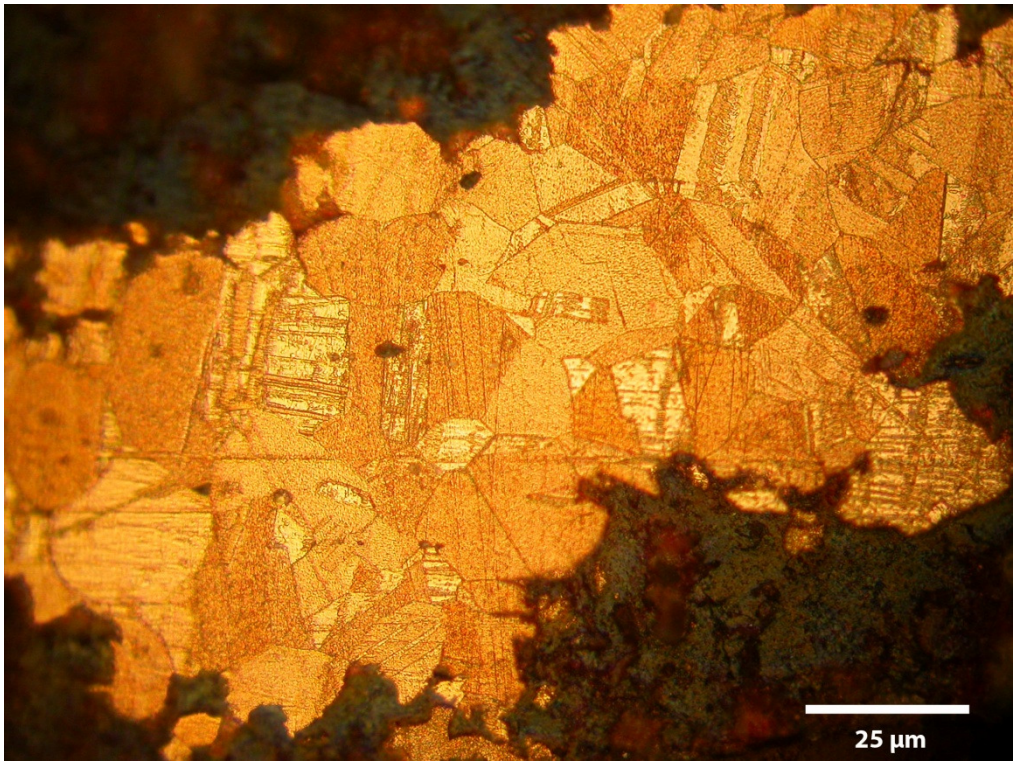

Figure A3.149 K10597

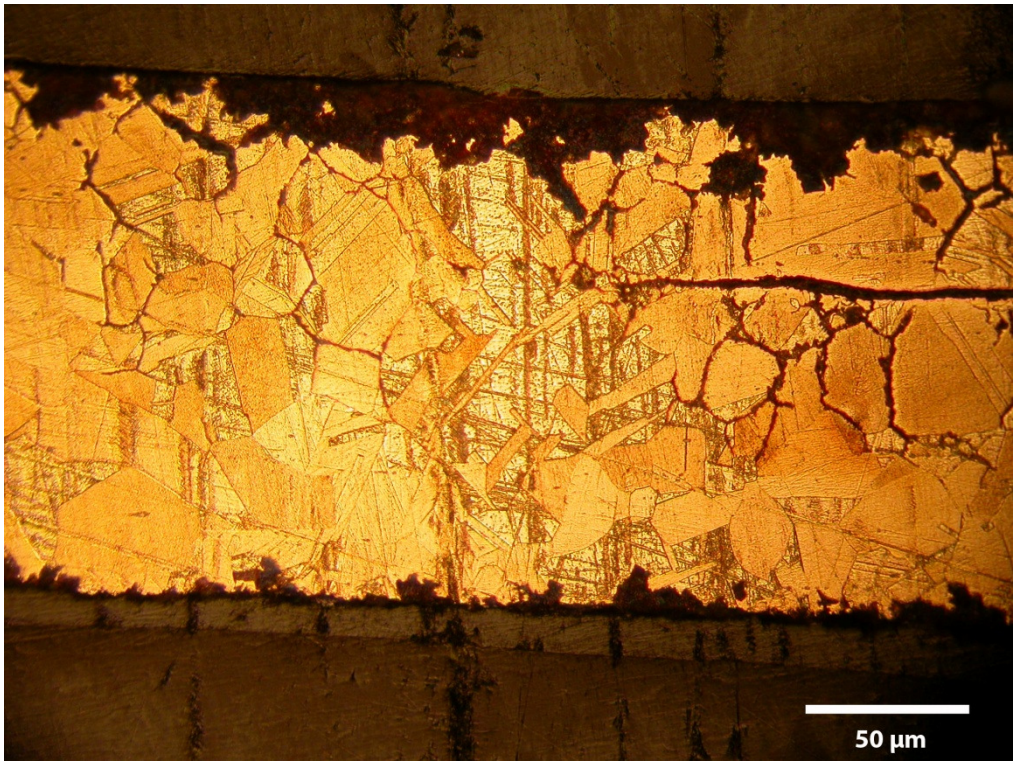

Figure A3.150 K11816

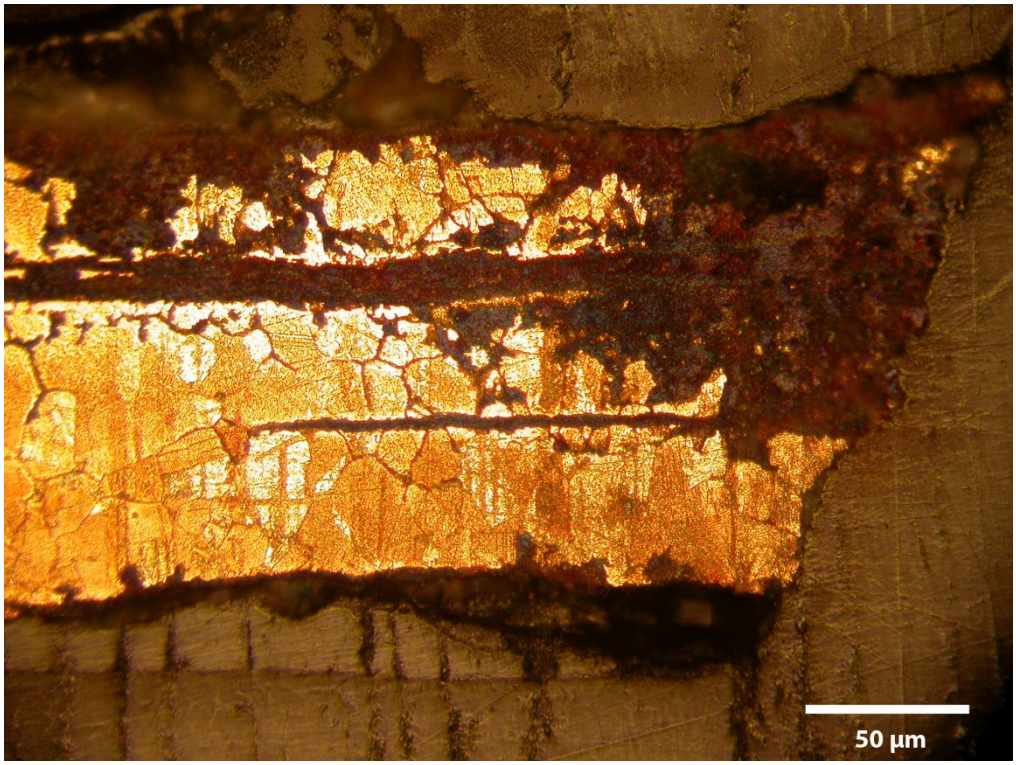

Figure A3.151 K11816

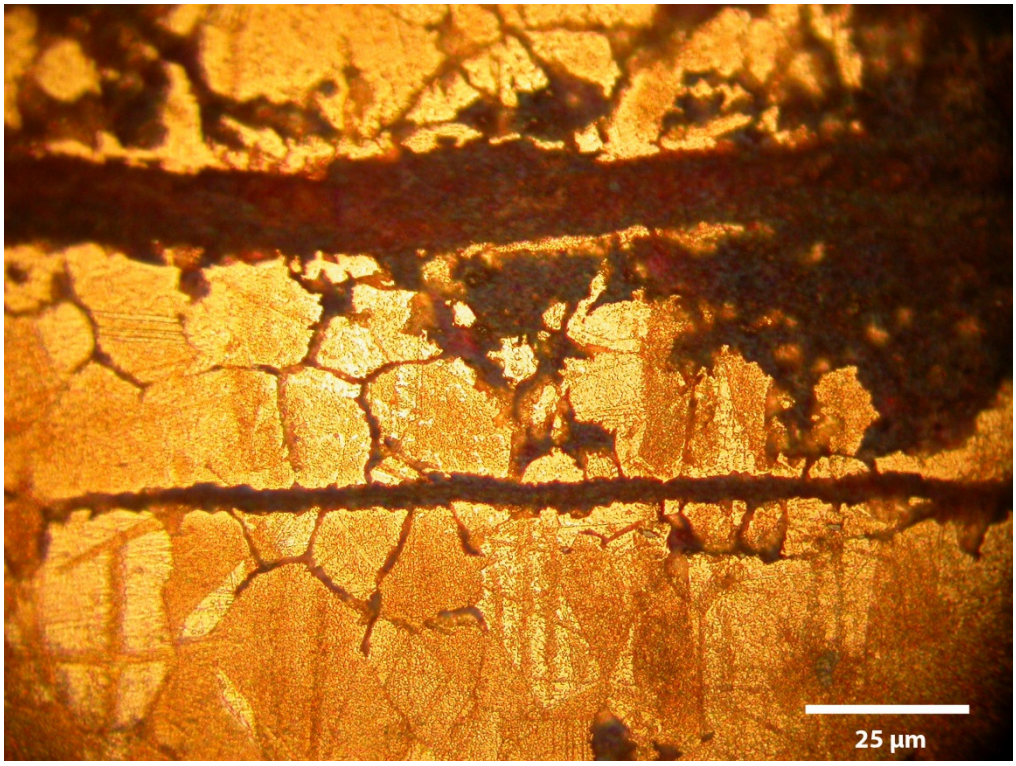

Figure A3.152 K11816

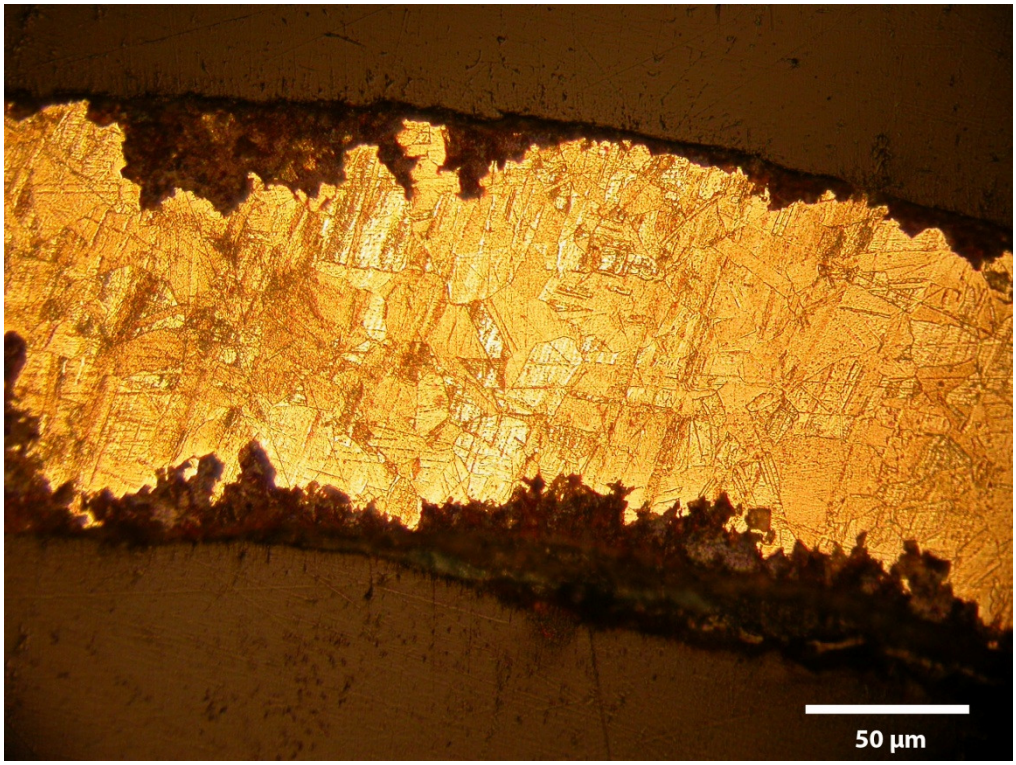

Figure A3.153 K13695E

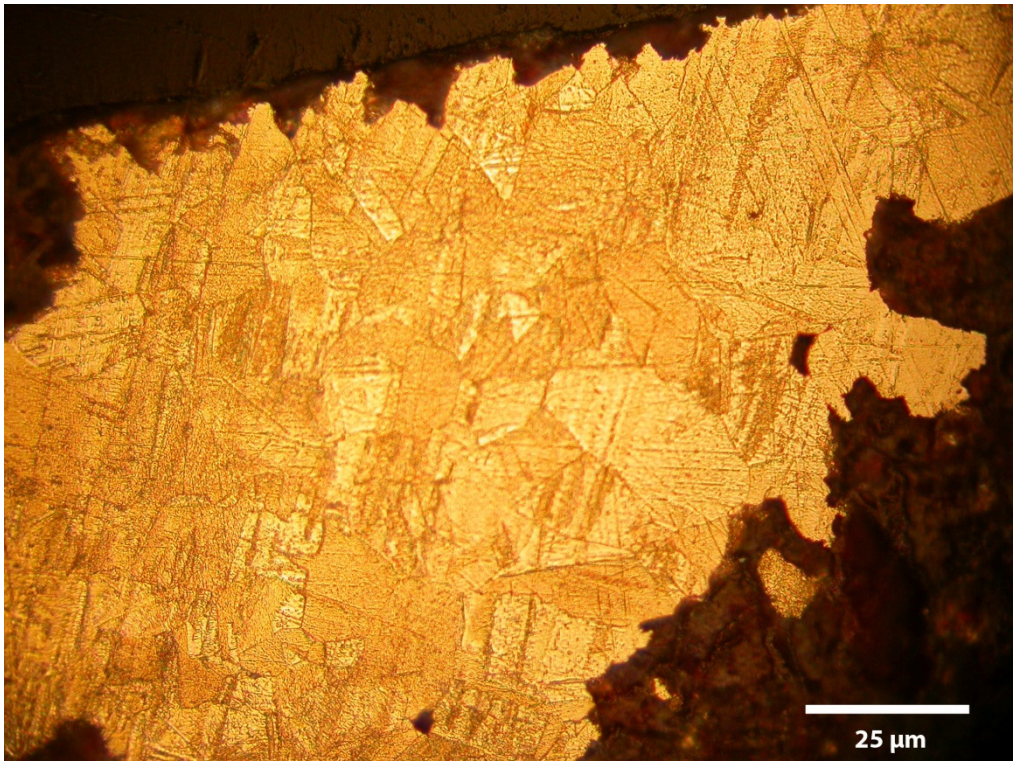

Figure A3.154 K13695E

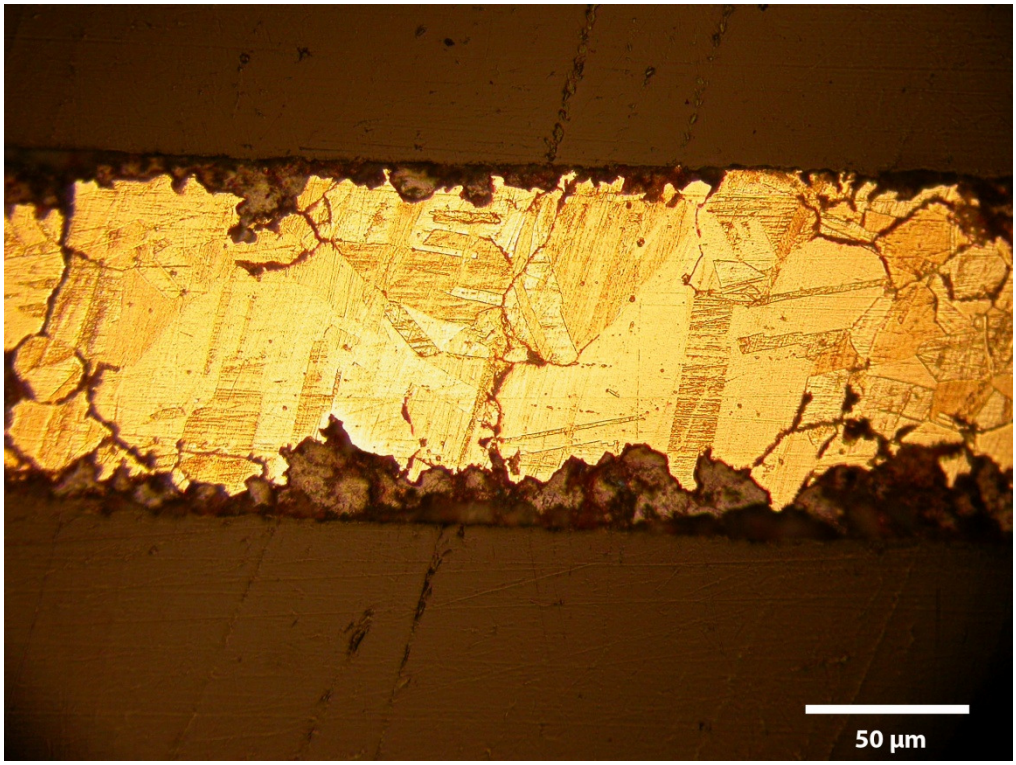

Figure A3.155 K22622

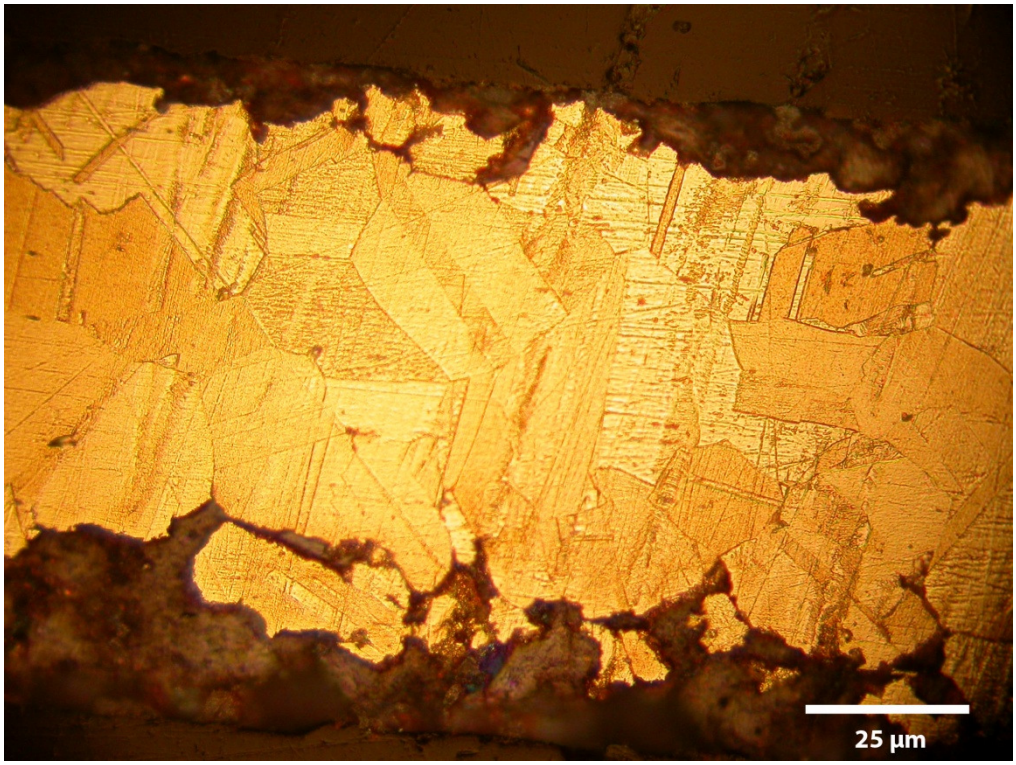

Figure A3.156 K22622

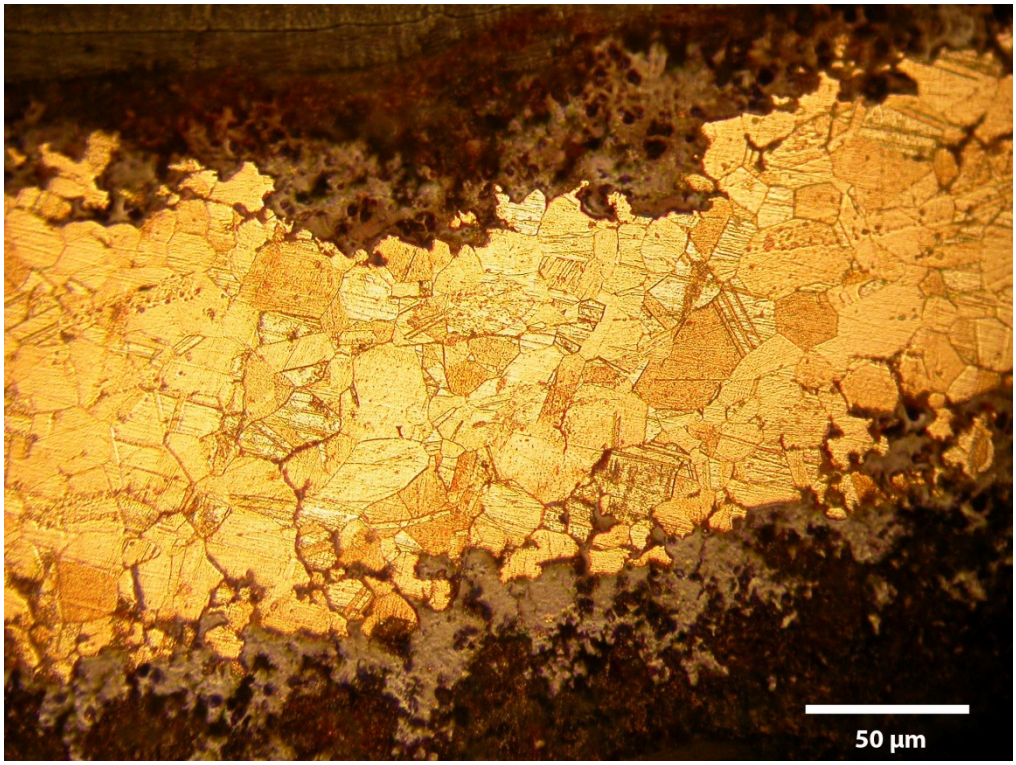

Figure A3.157 K22685

Figure A3.158 K22685

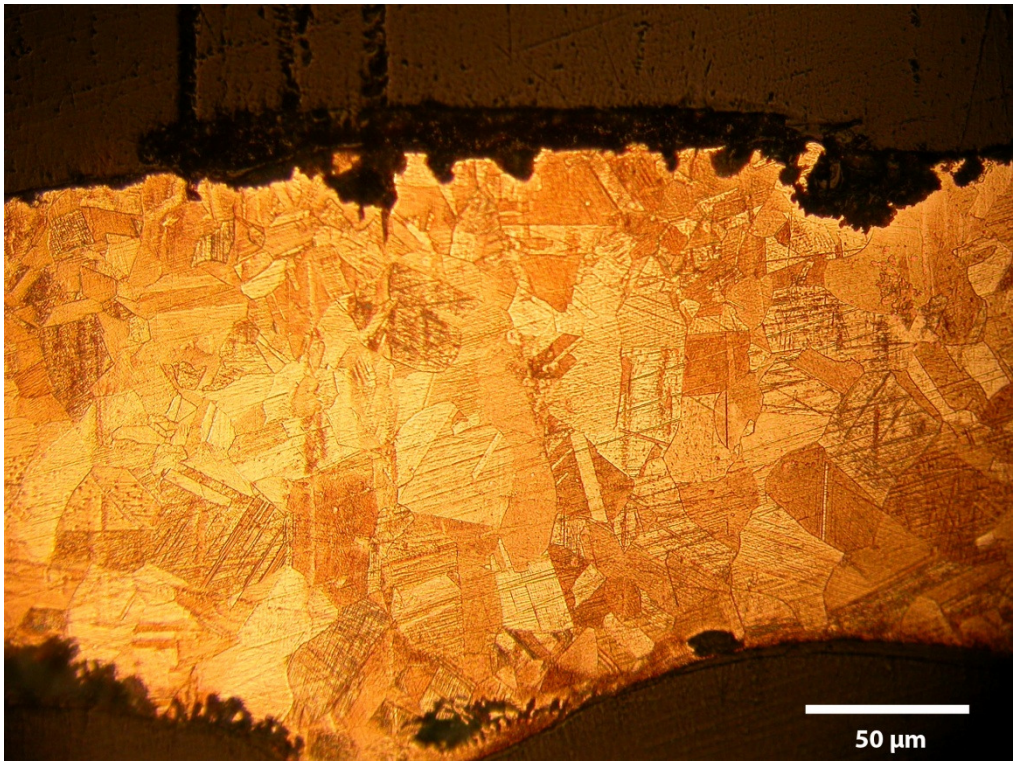

Figure A3.159 K33801

Figure A3.160 K33801

APPENDIX 4: EDS Results and comparison with AAS

CC113	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	77.50	0.37	0.18	21.4	0.1	<0.09	<0.09	0.2	0.1
AAS	77.15	0.83	0.71	21.8	0.372	0.003	0.001	0.103	0.42
variation %	1.36	55.27	93.05	25.72	63.13			60.09	66.62
CC136	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	80.29	0.42	0.33	18.4	0.4	<0.09	<0.09	0.1	0.1
AAS	77.3	0.16	0.15	21.78	0.393	0.004	0.008	0.221	0.64
variation %	3.87	156.52	123.2	15.52	10.21			70.57	90.25
CC153	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	81.16	0.53	0.39	17.1	0.4	<0.09	<0.09	0.1	0.2
AAS	78.57	0.92	2.56	17.03	0.336	0.012	0.001	0.099	0.34
variation %	1.29	76.05	556.41	0.29	15.95			19.87	64.28

Table A4.1 EDS Results and comparison with AAS for the objects from South Cadbury.

HamHE16	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	76.64	0.44	0.18	22.4	0.1	0.0	<0.09	0.1	0.1
AAS	76.03	0.34	1.19	22.24	0.07	0.09	0.010	0.010	0.07
variation %	0.8	28.77	84.67	0.55	24.62	53.65			94.44
HamH A1276	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	79.5	0.4	0.2	19.6	0.1	0.04	0.04	0.09	0.1

Table A4.2 Results and comparison with AAS for the object from Ham Hill.

CSL2042	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	81.1	0.3	2.0	15.7	0.5	0.2	<0.09	<0.09	0.2
AAS	82.7	0.4	1.505	16.2	0.286	0.019	<0.008	0.2	0.6
variation %	1.9	35.7	33	3.0	87.031	695.411			72.1
CSL2042	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	80.2	0.1	0.6	18.7	0.2	<0.09	<0.09	<0.09	0.2
AAS	82.7	<0.121	1.52	18.0	0.211	0.050	0.014	<0.074	0.5
variation %	3.0		60	4.3	2.534				55.8
CSL2788	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	82.8	1.9	2.1	12.7	0.5	<0.09	<0.09	<0.09	<0.13
AAS	76.2	3.2	8.1	11.6	0.331	0.023	<0.009	0.3	0.1
variation %	8.7	39.8	74.2	9.8	51.804				
CSL3946	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	89.7	0.3	0.7	8.9	0.3	0.2	<0.09	<0.09	<0.13
AAS	91.7	0.2	1.2	7.4	0.391	0.013	<0.007	0.1	<0.066
variation %	2.3	37.6	41.3	20.1	31.643	1044.648			
CSL3985	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	77.5	0.4	0.3	21.7	0.2	<0.09	<0.09	<0.09	<0.13
AAS	75.8	<0.108	1.3	22.8	0.149	<0.014	<0.008	0.2	0.5
variation %	2.3		79.9	4.8	37.536				
CSL4772	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	78.1	0.3	0.9	20.2	0.3	<0.09	<0.09	<0.09	0.1
AAS	75.4	0.2	3.0	21.5	0.191	<0.016	0.010	0.2	0.7
variation %	3.6	33.8	70.3	6.2	60.304				78.8
CSL4788	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	97.1	0.2	0.8	0.8	0.7	0.2	0.1	<0.09	0.1
AAS	98.5	0.3	1.3	<0.05	0.225	<0.014	<0.007	0.1	0.8
variation %	1.4	18.8	41.0		218.222				86.7
CSL6224	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	78.8	11.0	7.8	1.0	0.4	0.1	<0.09	<0.09	0.9
AAS	79.1	11.9	7.8	0.2	0.299	0.030	0.010	0.1	0.4
variation %	0.4	8.1	0.4	408.9	44.793	249.074			113.8

Table A4.3 EDS Results and comparison with AAS for the objects from Carlisle.

USKManFig3N7	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	78.2	0.2	0.1	21.2	0.27	0.06	<0.09	0.10	<0.13
AAS	78.3	0.1	<2.528	21.9	0.15	0.01	0.04	0.11	0.6
variation %	0.1	221.7			81.42	319.08			
USKManF4N8	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	80.0	0.2	0.1	18.7	0.48	0.02	<0.09	0.05	0.3
AAS	74.7	0.0	4.6	19.6	0.29	0.01	0.06	0.13	1.6
variation %	7.2	409.6	97.5	4.6	64.50	290.73			
USKManF5N36	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	82.5	0.2	0.5	16.3	0.31	0.09	<0.09	<0.09	0.1
AAS	82.6	0.0	1.1	16.5	0.19	0.01	0.04	0.08	0.5
variation %	0.2	270.7	56.1	1.3	57.51	1453.48			
USKManP40N3	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	80.7	1.0	1.1	16.3	0.78	0.05	<0.09	<0.09	<0.13
AAS	80.0	1.2	3.8	14.9	0.55	0.02	0.04	0.13	0.1
variation %	0.9	13.5	70.6	9.6	41.85	206.59			
USKManP40N8	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	82.9	3.7	11.1	1.4	0.38	<0.09	<0.09	<0.09	0.6
AAS	83.4	3.0	12.3	0.3	0.45	0.01	0.01	0.13	0.4
variation %	0.6	25.4	9.7	386.7	13.93				

Table A4.4 EDS Results and comparison with AAS for the objects from Usk.

CHE 3	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	72.62	5.65	6.31	14.19	0.62	0.08	0.03	<0.09	0.51
AAS	70.18	9.74	8.37	10.44	0.50	0.04	0.01	0.50	0.14
variation %	3.48	42.03	24.63	35.98	24.38	88.53	273.90		263.57
CHE 21	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	78.74	0.26	0.57	19.79	0.52	0.00	0.12	0.40	<0.13
AAS	81.39	0.10	1.50	16.25	0.29	0.01	0.01	0.29	0.11
variation %	3.26	161.42	61.90	21.81	75.96		1050.42	34.97	
CHE 57	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	77.17	10.95	8.98	2.40	0.44	0.02	0.04	<0.09	<0.13
AAS	74.74	15.08	9.08	0.09	0.34	0.04	0.01	0.33	0.21
variation %	3.26	27.43	1.03	2505.82	32.55	56.56	254.75		
CHE 142	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	84.97	0.45	5.37	8.54	0.49	0.16	0.02	<0.09	<0.13
AAS	85.34	0.55	6.28	6.90	0.40	0.02	0.01	0.40	0.07
variation %	0.43	17.52	14.44	23.76	24.67	611.16	68.21		
CHE 349	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	75.95	0.23	0.27	23.14	0.20	0.03	0.04	<0.09	0.06
AAS	89.79	0.00	1.33	8.62	0.07	0.00	0.02	0.07	<0.1
variation %	15.42		79.55	168.41	178.53	704.45	60.21	25.60	32.77
CHE 261	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	82.54	0.81	4.97	11.05	0.51	0.07	0.04	<0.09	<0.13
AAS	85.33	0.33	5.13	8.23	0.44	0.02	0.02	0.44	<0.1
variation %	3.27	148.67	3.07	34.39	16.05	230.86	131.59		
CHE 701	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	82.52	0.22	0.45	16.07	0.47	0.05	0.03	0.04	0.19
AAS	84.42	0.19	0.85	13.88	0.30	0.01	0.01	0.30	<0.1
variation %	2.25	14.15	46.78	15.78	59.51	348.16	137.74	87.26	2050.95
CHE 848	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	80.87	0.30	0.81	17.48	0.26	0.11	0.02	<0.09	0.15
AAS	81.58	0.22	2.84	14.86	0.14	0.02	0.01	0.14	0.12
variation %	0.87	40.07	71.45	17.60	82.62	544.25	85.23	98.23	31.90

Table A4.5 EDS Results and comparison with AAS for the objects from Chester (continues on next page).

CHE 1272	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	74.34	12.75	7.95	1.77	0.54	0.03	0.08	<0.09	2.53
AAS	74.83	14.97	8.84	0.02	0.55	0.03	0.01	0.55	<0.1
variation %	0.66	14.84	9.98	8049.98	1.41	2.59	590.23		
CHE 1513	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	78.55	0.33	0.51	20.09	0.28	0.07	0.00	<0.09	0.18
AAS	80.32	0.00	0.00	19.05	0.27	0.01	0.01	0.27	<0.1
variation %	2.21			5.48	3.63	433.62	86.22	85.07	
CHE 1516	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	72.24	14.22	6.89	4.78	0.81	0.15	0.03	<0.09	0.88
AAS	75.71	12.55	7.79	2.44	0.63	0.02	0.00	0.63	0.13
variation %	4.59	13.29	11.58	95.78	29.14	512.46	465.55		565.27
CHE 1829	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	82.37	0.42	1.16	15.67	0.28	0.06	0.05	<0.09	<0.13
AAS	83.88	1.07	1.96	12.49	0.17	0.02	0.01	0.18	0.18
variation %	1.81	61.04	40.74	25.43	62.48	208.37	502.98		
CHE 1833	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	79.49	0.53	0.98	18.06	0.56	0.04	0.02	<0.09	0.33
AAS	79.20	0.24	2.36	17.28	0.36	0.03	0.01	0.36	0.09
variation %	0.36	122.98	58.49	4.50	53.27	39.72	176.30		287.07
CHE 1834	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	79.42	0.25	1.35	18.57	0.26	0.00	0.03	<0.09	0.11
AAS	83.64	0.10	2.36	13.03	0.36	0.02	0.01	0.36	<0.1
variation %	5.04	160.02	42.72	42.49	28.61		203.68	98.89	
CHE 1850	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	86.01	0.60	7.23	5.12	0.78	0.05	0.05	<0.09	0.16
AAS	86.34	0.25	6.27	5.90	0.50	0.02	0.00	0.50	0.15
variation %	0.39	138.51	15.46	13.27	56.20	162.32	1004.26		11.80
CHE 1855	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	76.33	12.12	5.19	5.27	0.53	0.00	0.02	<0.09	0.54
AAS	70.81	18.75	7.68	1.85	0.36	0.02	0.01	0.36	<0.1
variation %	7.79	35.33	32.49	184.47	48.96		152.83		

Table A4.5 EDS Results and comparison with AAS for the objects from Chester (continues on next page).

CHE 2024	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	79.71	8.85	8.14	1.53	0.32	0.18	0.06	<0.09	1.22
AAS	72.40	16.91	10.37	0.07	0.07	0.02	0.01	0.07	<0.1
variation %	10.09	47.68	21.56	2007.10	325.25	609.79	532.76		
CHE 2171	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	79.71	1.53	8.14	8.85	1.22	0.32	0.06	0.18	<0.13
AAS	84.98	0.00	1.74	12.47	0.33	0.02	0.02	0.33	0.04
variation %	6.20		366.63	29.06	270.10	1590.21	289.94	46.16	
CHE 2711	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	80.18	0.51	2.13	16.17	0.42	0.13	0.01	0.00	0.45
AAS	81.96	0.82	3.01	14.07		0.03	0.01		<0.1
variation %	2.17	37.92	29.46	14.95		395.92	0.88		
CHE 8969	%Cu	% Pb	% Sn	% Zn	% Fe	% Ni	% Mn	% Sb	% As
EDS	78.70	12.38	7.10	0.60	0.27	0.14	0.03	0.00	0.79
AAS	74.03	17.90	7.54	0.01	0.06	0.03	0.01	0.06	0.26
variation %	6.32	30.85	5.85	5492.32	359.11	400.54	138.17		202.84

Table A4.5 EDS Results and comparison with AAS for the objects from Chester.

GLC48	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	73.8	1.7	0.1	24.1	0.32	<0.09	<0.09	<0.09	<0.13
AAS	76.7	2.1	0.1	20.7	0.17	0.05	<0.001	0.03	<0.05
variation %	3.8	17.9	8.8	16.2	86.29				
GLC161	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	81.1	0.3	0.2	18.2	0.23	<0.09	<0.09	<0.09	<0.13
AAS	81.9	0.1	0.1	17.7	0.12	0.02	0.00	<0.011	0.1
variation %	1.0	235.7	35.6	3.3	92.50				
GLC442	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	78.8	1.8	1.3	17.1	0.91	<0.09	<0.09	<0.09	<0.13
AAS	73.0	2.7	1.3	21.4	0.95	0.19	<0.001	0.25	0.1
variation %	8.0	31.1	4.1	20.2	4.59				
GLC813	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	94.5	0.3	3.0	1.6	0.40	<0.09	<0.09	<0.09	0.2
AAS	94.1	0.4	4.3	0.5	0.44	0.01	<0.0015	0.04	0.1
variation %	0.4	26.4	29.4	239.1	9.39				
GLC846	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	77.2	0.3	0.3	22.0	0.21	<0.09	<0.09	<0.09	<0.13
AAS	81.3	<0.039	0.3	18.2	0.09	0.01	<0.001	0.07	<0.054
variation %	5.1		6.5	20.9	138.89				
GLC1099	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	92.5	0.7	3.0	3.6	0.21	<0.09	<0.09	<0.09	
AAS	90.5	1.1	4.7	3.1	0.15	0.05	0.00	0.28	0.1
variation %	2.2	31.0	36.1	16.9	39.35				
GLC1176	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	81.0	1.9	3.2	13.0	0.95	<0.09	<0.09	<0.09	<0.13
AAS	82.5	2.2	3.4	10.7	0.91	0.02	<0.003	0.08	0.1
variation %	1.8	14.7	7.2	21.8	4.33				
GLC1234	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	75.0	0.3	0.3	24.0	0.15	<0.09	0.02	<0.09	0.2
AAS	76.2	<0.048	0.1	23.0	0.14	0.01	0.01	0.08	0.3
variation %	1.6		94.4	4.4	6.74		111.93		
GLC1376	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	83.1	0.5	2.5	13.1	0.4	0.12	<0.09	<0.09	0.2
AAS	83.8	0.1	3.6	11.7	0.38	0.16	<0.0016	0.02	0.3
variation %	0.9	646.9	29.0	12.3	10.44	24.35			

Table A4.6 EDS Results and comparison with AAS for the objects from Kingsholm (continues on next page).

GLC1489	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	77.5	0.7	1.2	20.0	0.7	<0.09	<0.09	<0.09	<0.13
AAS	75.1	1.5	2.0	20.4	0.61	0.28	<0.001	0.06	<0.059
variation %	3.1	53.7	43.4	1.9	11.74				
GLC1533	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	78.5	0.5	0.3	20.4	0.2	0.06	<0.09	<0.09	0.1
AAS	78.6	0.1	<0.084	21.1	0.13	0.01	0.002	0.04	<0.092
variation %	0.2	382.4		3.1	17.17	726.95			
GLC1573	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	76.8	0.2	0.5	22.4	0.1	<0.09	<0.09	<0.09	<0.13
AAS	77.1	0.1	0.4	22.2	0.13	0.01	0.004	0.04	<0.095
variation %	0.4	131.2	26.2	0.9	4.39				
GLC1683	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	90.6	0.3	8.6	<0.07	0.2	<0.09	<0.09	<0.09	0.3
AAS	90.0	0.1	8.8	0.0	0.18	0.06	0.002	0.49	0.4
variation %	0.7	399.5	1.8		2.15				
GLC1685	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	81.2	0.4	0.5	17.6	0.3	<0.09	<0.09		0.1
AAS	80.2	0.7	0.5	18.0	0.36	0.01	0.002	0.05	0.1
variation %	1.2	46.7	12.3	2.7	29.45				
GLC2136	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	99.5		0.2	<0.07	0.3	<0.09	<0.09	0.07	<0.13
AAS	99.3	0.1	0.2	0.1	0.17	0.02	<0.001	0.04	<0.119
variation %	0.2		23.3		93.55				
GLC2148	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	79.4		0.4	19.8	0.4	<0.09	<0.09	<0.09	<0.13
AAS	80.7	0.9	0.4	17.5	0.32	0.01	<0.003	0.11	<0.071
variation %	1.6		11.3	13.0	9.30				
GLC2290	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	81.7	0.7	0.5	16.3	0.6	0.31	<0.09	<0.09	<0.13
AAS	82.4	1.2	0.5	15.1	0.25	0.26	0.003	0.05	0.2
variation %	0.9	43.0	4.0	7.5	130.35	17.17			
GLC2357	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	78.8	0.6	1.8	18.4	0.4	<0.09	<0.09	<0.09	<0.13
AAS	79.0	0.9	2.2	17.3	0.31	0.02	<0.001	0.15	0.1
variation %	0.2	36.1	17.1	6.1	35.68				

Table A4.6 EDS Results and comparison with AAS for the objects from Kingsholm (continues on next page).

GLC2359	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	77.3	0.3	0.2	21.8	0.4	<0.09	<0.09	<0.09	<0.13
AAS	77.6	0.1	0.1	21.8	0.31	0.01	0.002	0.03	<0.047
variation %	0.4	225.8	73.6	0.1	43.48				
GLC2360	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	80.0	1.4	1.7	16.5	0.5	<0.09	<0.09	<0.09	<0.13
AAS	79.4	2.4	2.8	14.6	0.46	0.02	<0.001	0.16	0.2
variation %	0.7	43.7	40.6	13.3	14.67				
GLC2361	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	81.4	0.3	1.6	16.4	0.3	<0.09	<0.09	<0.09	<0.13
AAS	81.7	0.3	2.9	14.4	0.36	0.02	0.002	0.10	0.2
variation %	0.4	8.8	43.8	13.9	6.47				
GLC2378	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	80.8	0.3	0.2	18.3	0.4	<0.09	<0.09	<0.09	<0.13
AAS	81.0	0.1	0.1	18.2	0.30	0.02	0.003	0.06	0.1
variation %	0.3	299.4	28.0	0.9	39.19				
GLC2602	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	79.1	0.3	0.2	20.3	0.2	<0.09	<0.09	<0.09	<0.13
AAS	78.7	0.2	0.4	20.4	0.12	0.01	0.002	0.05	0.1
variation %	0.5	73.4	57.9	0.3	37.45				
GLC2693	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	82.6	0.7	0.5	15.2	1.0	<0.09	<0.09	<0.09	<0.13
AAS	83.2	1.1	0.8	13.8	0.95	0.04	0.003	0.04	<0.073
variation %	0.8	38.3	38.4	10.3	7.90				
GLC2741	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	92.2	0.8	4.2	2.5	0.3	0.11	<0.09	<0.09	<0.13
AAS	90.7	1.3	5.7	1.9	0.11	0.03	0.002	0.18	<0.105
variation %	1.6	42.1	25.4	28.6	161.38	304.86			
GLC2936	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	80.9			18.8	0.2	0.04	<0.09	<0.09	<0.13
AAS	80.8	0.1	0.1	18.7	0.19	0.01	0.002	0.05	<0.051
variation %	0.1			0.6	11.64	214.31			

Table A4.6 EDS Results and comparison with AAS for the objects from Kingsholm

K186	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	98.17	0.69	0.94	<0.07	0.15	<0.09	0.05	<0.09	<0.13
AAS	99.00	0.40	<0.092	<0.015	0.01	0.10	<0.0016	0.11	0.27
variation %	0.84	74.59			2224.46				
K742	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	77.67	0.27	0.21	21.48	0.24	<0.09	0.02	<0.09	0.11
AAS	78.54	0.18	0.15	20.54	0.15	0.02	0.01	0.04	0.31
variation %	1.11	49.88	38.95	4.58	57.85		120.55		
K2002	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	79.90	0.30	0.28	19.29	0.23	<0.09	<0.09	<0.09	<0.13
AAS	77.37	0.09	0.32	21.90	0.18	0.03	0.001	0.01	<0.047
variation %	3.27	220.21	13.68	11.88	24.76				
K2030	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	78.92	0.47	0.34	19.89	0.22	<0.09	<0.09	<0.09	0.17
AAS	79.80	0.11	0.40	19.05	0.17	0.03	0.001	0.22	0.16
variation %	1.10	338.81	15.49	4.41	31.95				
K3223	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	78.13	0.39	0.39	20.73	0.36	<0.09	<0.09	<0.09	<0.13
AAS	77.70	0.08	0.34	21.69	0.14	0.03	0.00	<0.013	<0.062
variation %	0.55	365.47	16.02	4.41	163.34				
K3797	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	78.99	0.33	0.56	19.46	0.39	0.18	0.08	<0.09	<0.13
AAS	76.58	0.23	0.17	22.73	0.18	0.01	0.01	0.02	<0.098
variation %	3.14	44.28	240.29	14.40	115.98	1893.69	993.03		
K10282	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	78.24	0.34	0.37	20.85	0.20	<0.09	<0.09	<0.09	<0.13
AAS	79.40	0.43	0.37	19.55	0.09	0.10	<0.003	0.04	<0.06
variation %	1.46	20.18	1.02	6.67	119.07				
K10412	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	77.70	0.71	0.29	21.00	0.20	0.10	<0.09	<0.09	<0.13
AAS	79.40	0.43	0.37	19.55	0.09	0.10	<0.003	0.04	<0.06
variation %	2.14	67.03	20.58	7.42	114.56	2.16			

Table A4.7 EDS Results and comparison with AAS for the objects from Kalkriese (continues on next page).

K10413	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	76.83	1.05	0.31	21.45	0.26	0.11	<0.09	<0.09	<0.13
AAS	79.40	0.43	0.37	19.55	0.09	0.10	<0.003	0.04	<0.06
variation %	3.24	146.14	17.25	9.76	173.83	5.15			
K10550	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	76.89	0.20	0.24	22.42	0.21	<0.09	0.01	<0.09	0.02
AAS	76.16	0.22	0.27	23.01	0.14	0.03	<0.0014	0.05	<0.092
variation %	0.96	7.20	11.81	2.56	55.64				
K10597	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	73.78	0.41	6.52	19.16	0.13	<0.09	<0.09	0.37	<0.13
AAS	76.51	0.34	0.60	22.33	0.10	0.07	<0.0015	0.02	<0.098
variation %	3.56	20.44	984.25	14.20	30.45				
K11816	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	80.54	0.22	0.31	18.69	0.23	<0.09	<0.09	<0.09	<0.13
AAS	77.86	0.06	0.31	21.55	0.17	0.02	0.001	<0.01	<0.046
variation %	3.44	251.66	1.24	13.26	39.61				
K13695E	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	77.81	0.19	0.24	21.38	0.34	<0.09	0.04	<0.09	<0.13
AAS	77.80	0.09	0.47	21.40	0.14	0.05	0.02	0.05	0.18
variation %	0.01	117.77	48.77	0.08	143.63		137.33		
K22622	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	75.40	0.30	0.33	23.48	0.22	<0.09	<0.09	<0.09	0.28
AAS	78.79	0.14	<0.107	20.67	0.11	0.03		0.05	0.13
variation %	4.31	99.62	142.15	83.48	98.91				
K26855	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	79.50	0.28	0.21	19.70	0.30	<0.09	<0.09	<0.09	<0.13
AAS	79.23	0.06	0.09	20.45	0.14	0.01	<0.001	<0.011	<0.048
variation %	0.34	407.16	123.36	3.65	115.64				
K33801	%Cu	%Pb	%Sn	%Zn	%Fe	%Ni	%Mn	%Sb	%As
EDS	89.94	0.00	9.82	<0.07	0.24	<0.09	<0.09	<0.09	<0.13
AAS	85.63	<0.023	14.21	<0.025	0.12	0.01	<0.003	0.02	<0.063
variation %	5.03		30.91		96.92				

Table A4.7 EDS Results and comparison with AAS for the objects from Kalkriese.